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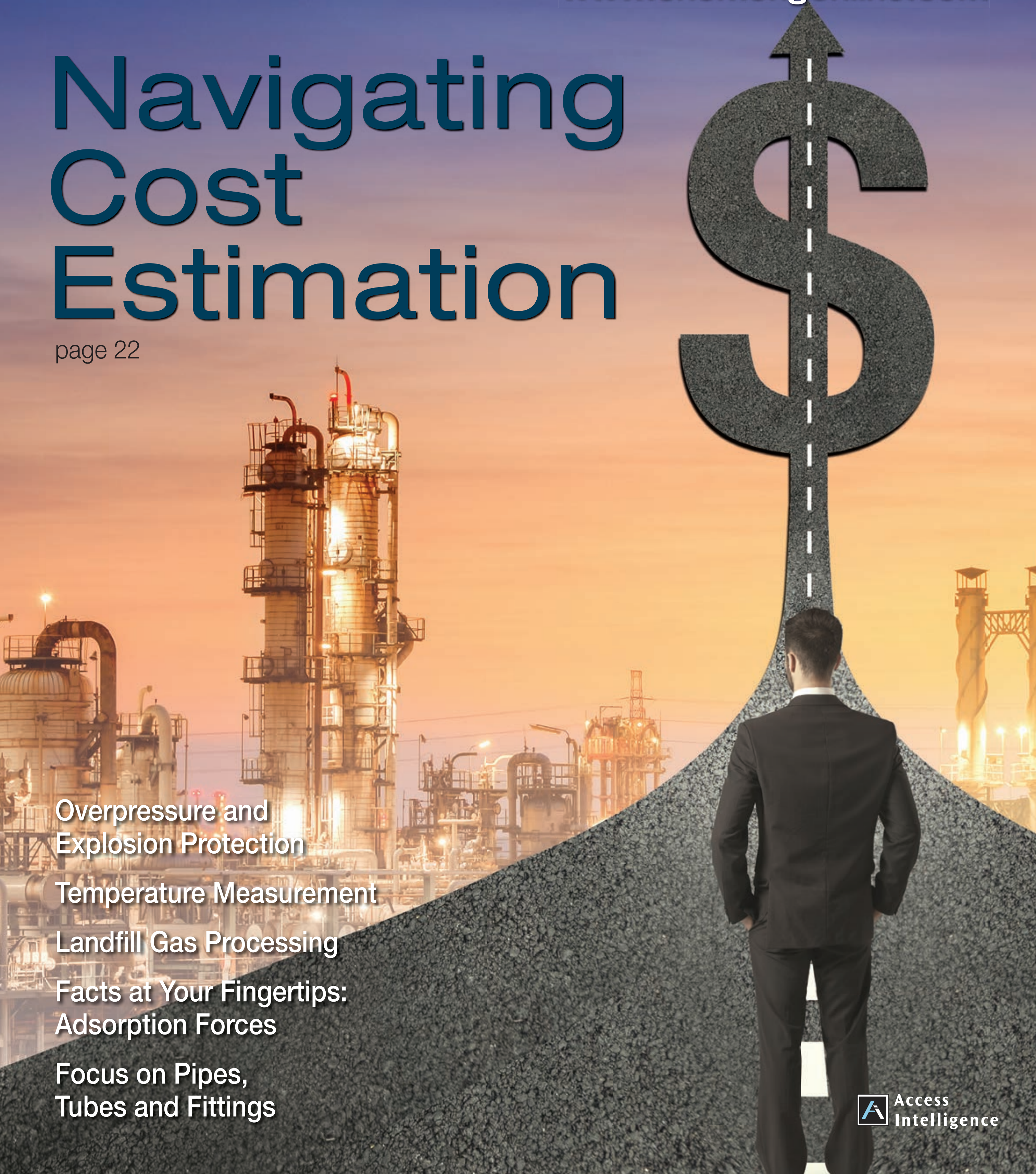

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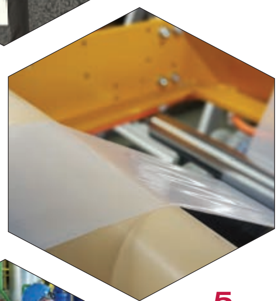

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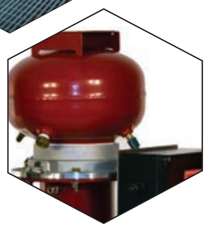

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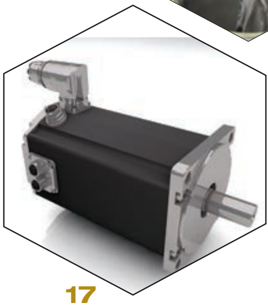

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Cover design: Tara Bekman

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Editor's Page

Announcing the Kirkpatrick finalists

Five innovative technologies have been selected as finalists for the 2021 Kirkpatrick Award for Chemical Engineering Achievement.* The finalists were selected based on three criteria: the difficulty of chemical engineering problems met and solved; novelty of the technology; and evidence of commercial success. The winner of the award will be announced later this year. Here is a brief summary of the finalists:

BQE Water — Selen-IX Technology. BQE Water developed the Selen-IX technology to remove selenite from wastewater in response to environmental concerns associated with selenium. Selenate is the most prevalent form of selenium in wastewater. The novelty of the process technology is the unique integration of ion exchange and electroreduction. Using this technology, selenate is removed from the wastewater and fixed into stable non-toxic solids. After three pilot tests for different mining projects, the first full-scale plant was commissioned in 2020, and two more plants are currently under construction.

Dow Industrial Intermediates & Infrastructure — Syntegra Solvent-Free Polyurethane Dispersion. Syntegra is a solvent-free polyurethane dispersion (PUD) developed by Dow for the production of artificial leather. A significant advantage of Syntegra is that it eliminates the use of hazardous solvents in the production of artificial leather. Dow is able to produce Syntegra in a continuous process rather than batchwise, which improves consistency in the product. Syntegra was commercially launched in 2020, and there is indication that this product can also help with CO_2 reduction goals.

Dow Deutschland — Walocel Cellulose-Ether Product. Cellulose ethers are used in dry-mortar cementitious tile adhesives in order to ensure the water retention that is needed to bond the tile and substrate. The water retention efficiency improves with the polymer's molecular weight. Walocel is a cellulose ether obtained by long-chain branching, and thereby reduces dosage reduction in mortars by up to 25%. Development of the production process involved significant studies of key reaction-engineering variables and the design and installation of some tailor-made systems. The product is said to be the first commercial-scale cellulose ether of its kind.

Haldor Topsoe — Hydrotreating Catalyst TK-6001 HySwell. TK-6001 HySwell is an alumina-supported NiMo hydrotreating catalyst. NiMo catalysts are in demand for ultra-low-sulfur diesel and hydrocracker pretreatment. Until now, unsupported catalysts have been the only type that could meet the high activity needed for these applications. Topsoe has developed catalyst preparation techniques to produce a stable, supported catalyst that can be regenerated. HySwell was launched in 2019 with reported excellent performance.

Sapphire — FreeSpin Turboexpander Generator. Sapphire Technologies, a subsidiary of Calnetix Technologies, has developed an axial flow-through, magnetic bearing, turboexpander generator for pressure-reduction energy recovery. The FreeSpin In-line Turboexpander (FIT) generator recovers high-pressure energy at pressure reduction stations and converts it into electricity. A first installation in Italy in 2019 was followed by two additional installations early this year in Japan. It is expected that FIT can play a key role in maximizing the efficiency of gas energy consumption and reducing CO_2 emissions. ■

Dorothy Lozowski, Editorial Director

* *For more about the Kirkpatrick Award, see www.chemengonline.com/kirkpatrick-award/*

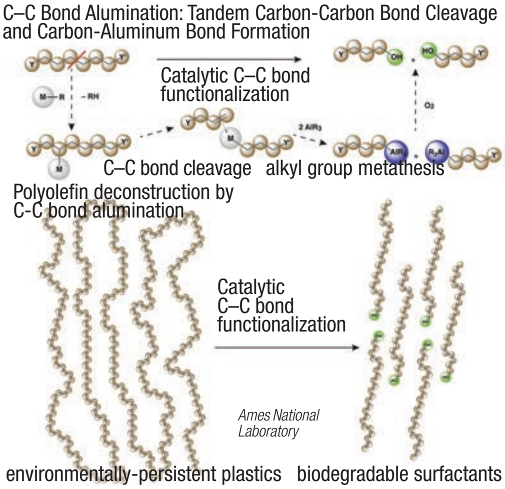
Polyolefin deconstruction process could provide new use for post-consumer plastic waste

Edited by:
Gerald Ondrey

A catalytic process to selectively break carbon-carbon bonds within the polymer chains of polyethylene and polypropylene could allow the use of waste plastics to make biodegradable surfactant molecules. Researchers led by the Institute for Cooperative Upcycling of Plastics (iCOUP) at the U.S. Department of Energy's Ames National Laboratory (Ames, Iowa; www.ameslab.gov) developed the process, which catalytically cleaves polymer chains into shorter units by introducing organo-aluminum end groups. The scientists can then functionalize these end groups to make biodegradable fatty alcohols, carboxylic acids or other derivatives.

The transformation (diagram) is enabled by C–H bond activation and ß-alkyl elimination reactions, in which a silica-supported zirconium catalyst forms a metal-alkyl intermediate that breaks C–C bonds within the polymer chain. Then, the complex is treated with tri-alkyl aluminum, forming shorter chain fragments with a triethylaluminum or tributylaluminum group at one end. The carboaluminum species can be derivatized using oxygen or other reagents to make fatty alcohols or carboxylic acids.

"Using Zr catalysts that are dispersed on a silica surface, we can essentially reverse the mechanism used to polymerize olefins into plastics — instead of forming new C–C bonds, we are cleaving them," explains Aaron Sadow, iCOUP director. "The alkylaluminum species that are formed allow upcycling of waste plastics, because they can be functionalized using known methods."



Ames National Laboratory

A technoeconomic analysis conducted at Argonne National Laboratory suggests the costs of producing fatty alcohols from waste plastic would be comparable to conventional synthesis of these molecules. At iCOUP, fatty alcohols have been synthesized using polyethylene shopping bags with no pre-treatment.

The research team is exploring how the design of the catalyst and support can be used to control the distribution of chain lengths in the fatty alcohol products. "We are trying to figure out how to maximize yields of C10–C20 chain lengths, because there is an existing market for those," Sadow says, "But there also could be new markets in the future for longer-chains, like C30s, because you could produce them from waste plastic at costs similar to conventionally made C12 chains, for example."

Harvesting Li from seawater electrochemically

Although the oceans contain about 5,000 times more lithium than what is found on land, the low concentrations (about 0.2 parts per million (ppm)), as well as the predominance of other larger ions (sodium, magnesium and potassium) makes Li extraction difficult. Now, researchers from King Abdullah University of Science and Technology (KAUST; Thuwal, Saudi Arabia; www.kaust.edu.sa) have developed an economically viable system that can extract high-purity lithium from seawater.

As described in a recent issue of *Energy & Environmental Science*, the KAUST team developed an electrochemical cell featuring a solid-state electrolyte membrane — a ceramic membrane made from lithium lanthanum titanium oxide (LLTO). This membrane's crystal structure has holes just wide enough to let Li^+ ions pass through, while blocking larger metal ions. The electrochemical cell contains three compartments. Seawater flows into a central feed chamber, where Li^+ ions pass through the LLTO membrane into a side compartment that contains a buffer solution and a copper cathode coated with platinum and ruthenium. Meanwhile, negative ions exit the feed chamber through a standard anion-exchange membrane, passing into a third compartment containing a NaCl solution and a Pt-Ru anode.

The system has been shown to enrich lithium from seawater from the Red Sea by 43,000 times — boosting the concentration from 0.2 ppm to more than 9,000 ppm, with a Li/Mg selectivity of over 45 million. Li_3PO_4 with a purity of 99.94% — sufficient for battery manufacturing — is formed by precipitation. The value of gases produced by the cell (H_2 at the cathode, Cl_2 at the anode) would more than offset the cost of electricity, which is estimated at $5 per 1 kg of Li extracted.

EXTRACTING Li

Doosan Heavy Industries & Construction, Ltd. (Changwon, South Korea; www.doosanheavy.com) has developed technology for recovering lithium carbonate from waste batteries. Li_2CO_3 is a key material that is used in batteries in electronic devices, such as laptops and mobile phones.

Conventional methods for extracting Li_2CO_3 from spent batteries involves heat-treatment, acid leaching and crystallization, which usually involve the use of chemicals such as sulfuric acid. In contrast, Doosan's method does not use any chemicals. Instead, the battery materials first undergo a heat treatment, followed by an electro-absorption crystallization process, which uses only distilled water to recover the Li_2CO_3.The technology — developed by Doosan and for which a patent has been filed — has the benefit of being simpler and more economical than existing methods, and is also environmentally friendly since no chemicals are used.

Starting in the second half of this year, Doosan will begin a demonstration project for a facility that will process 1,500 ton/yr of spent batteries and produce Li_2CO_3 with a 99% purity. "We plan to aggressively target the domestic used-battery recycling market, which is forecast to grow rapidly to the size of 19,000 tons by 2029," says Yongjin Song, the company's chief scientific officer.

HYDROGENATION

A few studies have shown that hydrogenation catalysis can be

(Continues on p. 6)

promoted by applying electric potentials to the catalyst. While these methods have already improved the selectivity and activity of heterogeneous catalysts under static conditions, the use of dynamic external stimuli has been underexplored.

Now, a team of scientists, led by associate professor Yan Ning from the Dept. of Chemical and Biomolecular Engineering at the National University of Singapore (NUS; www.nus.edu.sg), has demonstrated a method to increase the rate of ethylene hydrogenation by a factor of five, compared to typical industrial rates. The technique developed by NUS researchers applies oscillating electric potentials to a commercial hydrogenation catalyst, which then dramatically increased the hydrogenation rate of ethylene to ethane.

"Such enhancements in the rates or selectivity of chemical reactions are instrumental in making a chemical process more efficient," says Yan. "Our work demonstrates a more direct and cost-effective way of optimizing catalyst performance that is beyond conventional methods," he says.

The study was published in a recent issue of the *Journal of the American Chemical Society.*

NAPHTHA

Axens (Rueil-Malmaison, France; www.axens.net) and Sulzer Chemtech's (Winterthur, Switzerland; www.sulzer.com) GTC Technology business have formed an alliance to license an advanced process for FCC (fluid catalytic cracking) naphtha processing. The combined offering

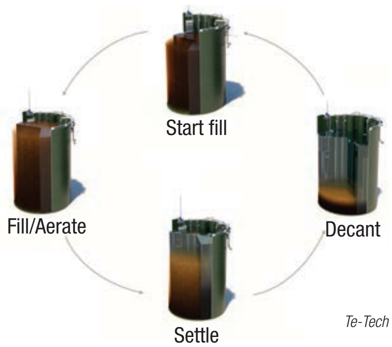
(Continues on p. 7)

Combine three steps in one unit with this wastewater-treatment process

A cyclic activated-sludge (AS) process, trademarked te-cyc, combines biological treatment and solids settlement in a single treatment step, thereby significantly reducing the footprint compared to a conventional AS plant, which requires three separate processes — primary settlement tanks, aeration tanks and final settlement, says Ben Hazard, a process engineer at Te-Tech Process Solutions, Ltd. (Totton, Southampton, U.K.; www.te-tech.co.uk). "This ultimately results in a lower capital cost due to less infrastructure being required."

The first plant of this kind was completed in 1999 at Neubrandenburg, Germany, with a nominal capacity of 140,000 PE (population equivalent). Now, Te-Tech Process Solutions has developed a modular unit that has been specifically designed for small- to medium-sized treatment works, which offers the same benefits of the larger plants, but at a smaller scale and with a design for manufacture and assembly approach in mind.

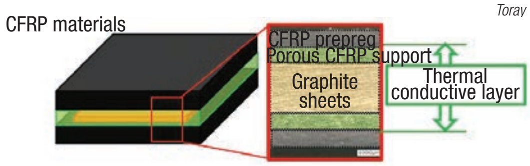
The te-cyc process is fundamentally based on a traditional sequencing batch reactor (SBR) whereby a sequence of tank filling, wastewater aeration, solids settlement and treated effluent decanting is repeated on a continuous cycle, explains Hazard. In the te-cyc process (diagram), there is typically 2 h of simultaneous filling and aerating, 1 h of settlement and 1 h of decanting. In the standard design, there will always be two or more tanks in parallel with their operating cycles out of phase with each other. This allows for a continuous inflow into the process as a whole, therefore eliminating the need for an upstream buffer tank, which would require energy-consuming mechanical mixing, says Hazard.



Te-Tech

"Unique to the te-cyc process is the inclusion and design of an anaerobic selector zone, internal return activated sludge pump and bespoke mechanically driven decanter," Hazard continues. The combination of the anaerobic selector zone and internal recycle suppresses the growth of poorly settling filamentous bacteria and promotes the growth of floc-forming bacteria that aggregate and form a large macrofloc. These macroflocs are larger than the typical flocs formed in conventional AS or SBR processes, and as such provide two key benefits: 1) the increased size leads to a quicker and more effective settlement of solids; and 2) the macroflocs are large enough to consist of an external aerobic zone and an internal anaerobic/anoxic zone, explains Hazard. "This means that nitrification and denitrification can occur simultaneously in the aeration phase of the te-cyc operation cycle," he says.

This carbon-fiber composite material is good at dissipating heat



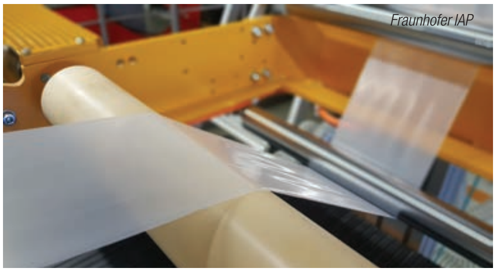
Toray

A technology that increases the heat-dissipating properties of carbon-fiber-reinforced plastic (CFRP) to that of metals has been developed by Toray Industries, Inc. (Tokyo, Japan; www.toray.com). Applying this technology to CFRP dissipates heat effectively from their sources through thermal conduction paths inside that material. This can help suppress battery degradation in mobility applications while boosting performance in electronic device applications, says the company.

CFRP is less thermally conductive than aluminum alloys and other metals. This has prompted efforts to enhance heat dissipation by employing external or internal graphite sheets offering excellent thermal conductivity and heat dissipation and diffusion. However, these sheets are easy to fracture, scatter and damage, which compromises the performance of CFRP.

Toray has created a heat-conductive layer employing a porous CFRP support that safeguards the graphite sheets (diagram). Laminating CFRP prepreg on this thermally conductive layer enabled Toray to attain a thermal conductivity above that of metals, which would be impossible with regular CFRP, without compromising the mechanical properties and quality of that material. Prepreg is a sheet-like intermediate material made by impregnating fibers with resin to reinforce them. The company was able to determine the thickness and lamination positions of graphite sheets that form thermal conduction paths. This enabled a flexible thermal management design, which controls the paths to release or use heat, for CFRP cooling efficiency and heat-diffusion paths.

Embedding active enzymes into plastics



Researchers at the Fraunhofer Institute for Applied Polymer Research (IAP; Potsdam-Golm, Germany; www.iap.fraunhofer.de) have developed a process for embedding active enzymes into plastics. This has been difficult before, since plastics are normally processed at temperatures above 100°C. The technology offers the possibility of manufacturing materials that clean themselves, have anti-mold surfaces or are self-degrading, for example.

The new materials are being developed as part of a project running since summer 2018, in cooperation with The Brandenburg University of Technology (BTU; Cottbus-Senftenberg, Germany).

In order to stabilize the enzymes, the researchers use porous inorganic carriers. "The enzymes bind to these carriers by embedding in the pores," explains Ruben R. Rosencrantz, head of the Biofunctionalized Materials and (Glyco)Biotechnology department at Fraunhofer IAP. "Although this restricts the enzymes' mobility, they remain active and are able to withstand much higher temperatures," he says.

The researchers then found a way to apply the stabilized enzymes not only to the surface of the plastic, but of embedding them into the plastics directly. In order to achieve an optimum material result in the downstream process, the stabilized enzymes have to be distributed as quickly as possible in the hot plastic melt to which they are added, without becoming exposed to excess force or elevated temperatures. "We have developed a process that is suitable for both bioplastics and for conventional petroleum-based plastics such as polyethylene," says Thomas Büsse who heads the institute's processing pilot plant for biopolymers in Schwarzheide.

So far, the researchers have mainly evaluated protease enzymes, which are able to break up other proteins. This lends the plastic functionalized by these proteases a self-cleaning effect. Pipes, for example, would not close up or clog as readily. Other enzymes are also being systematically tested as well. The partners at BTU Cottbus-Senftenberg are focusing more closely on enzymes for degrading plastics and toxic substances, for example. The first functionalized plastic granulates, films and injection molding bodies have already been produced in a pilot plant in Schwarzheide (photo).

Scaling up a recycling process for blended textile fibers

In order to handle the growing volume of waste textile materials, recycling processes must begin significantly scaling up. Lenzing AG (Lenzing, Austria; www.lenzing.com) and Södra (Växjö, Sweden; www.sodra.com) are joining forces to scale up the OnceMore textile-recycling process, which is said to be the world's first industrial-scale recycling technology for textiles with blended fibers, which are typically seen as difficult to efficiently recycle.

"OnceMore is able to simultaneously degrade polyester while retaining the cotton or cellulosic part of the material. Today, the process accepts textiles containing up to 50% polyester. Since polyester-cotton is one of the most abundant textile blends, we can process many types of post-consumer waste, including bedsheets, napkins, towels and garments," explains Johannes Bogren, vice president of Södra's Cell Bioproducts division. Furthermore, OnceMore is capable of large-scale production because it is able to use existing pulp-mill equipment says Bogren. The process blends waste textiles with wood cellulose to create a dissolving high-alpha-cellulose pulp product that can be processed into new textile products. The OnceMore technology has successfully processed 25 tons of textile waste in one day, and the company is now working to replicate that performance and begin using OnceMore pulp as a raw material for the production of Lenzing's Tencel x Refibra specialty fibers.

Lenzing and Södra's partnership aims to increase the share of recycled content in OnceMore pulp from 20% up to 50%, significantly increasing the production capacity. "For our target of recycling 25,000 tons of textiles by 2025, we will need a working, sorting and collecting system for discarded textiles. People need to stop throwing their textile waste in the garbage. Technology-wise, we need to expand our specification for what we can accept — we will need ways to handle zippers, prints, various trims and assorted fibers like wool, elastane and nylon," adds Bogren.

is based on Axens' Prime-G+ hydrodesulfurization technology and Sulzer Chemtech's GT-BTX PluS extraction technology.

The combination of Prime G+ and GT-BTX PluS offers a unique solution to reduce octane loss to a very low level for the gasoline pool. The technology is especially important in countries that are upgrading fuel specifications to meet environmental requirements, and it can be applied in new, or retrofits of existing units in operation to maximize profit. It also provides refiners the option of converting FCC gasoline into petrochemical products — benzene, toluene, xylenes (BTX) and additional propylene — and get additional margin in regions where gasoline demand is not sufficient. For those, the combined offer can convert their excess gasoline into petrochemical products to adapt to the market change with minimum investment, say the companies.

TRANSPORTING H_2O_2

Evonik Industries AG (Essen, Germany; www.evonik.com) has developed a container made of pure aluminum with a 220-L capacity for the safe transport of high-concentration hydrogen peroxide. With this patented container, the company is closing a logistical gap that had opened up in the safe delivery of highly concentrated H_2O_2 to users in the aerospace industry. Up to now, only very small containers (up to 12.5 L) were available.

The new container is installed in a lattice box with a protective steel frame to protect the actual container from damage during transport. The pure aluminum in the inner tank serves to ensure the quality of the H_2O_2.

H_2O_2 in concentrations of 82.5 to 98% has been used as a propellant for rocket engines since the mid-20th century. With Propulse, Evonik is supplying a high-concentrated H_2O_2 for this

(Continues on p. 8)

purpose, which is more powerful and easier to handle in comparison with other fuels.

PP FROM CARPET WASTE

Researchers from the Fraunhofer Institute for Building Physics (IBP; Stuttgart, Germany; www.ibp.fraunhofer.de) and partners have developed a solvent-based process that recycles carpet waste into virgin-grade polypropylene (PP). Developed as part of the Isoprep project, which is funded under the E.U.'s Horizon 2020 program, the process is based on an ionic liquid that selectively dissolves PP, leaving behind dyes and other additives. As a result, the PP can be reused for making new products rather than the standard practice of being incinerated, or down-cycled for lower-grade products.

The process has been demonstrated at the laboratory scale involving several liters of the solvent. A pilot plant capable of recycling 1 ton/d of carpet waste is planned to start up by the end of the project in March 2022.

BIOSURFACTANTS

A process that integrates fermentation and separation is being scaled up to produce biosurfactants. Developed by Holiferm (Manchester, U.K.; www.holiferm.com), the process is based on a fermentation using a natural yeast derived from a Canadian honey bee hive, using vegetable oil and glucose as raw materials. Sophorolipids, the product of the fermentation, are subsequently recovered by an integrated separation process based on gravity and phase separation.

Last April, the company installed a 600-L pilot production plant in Daresbury and completed its first batch, which produced hundreds of kilograms of sophorolipid. The products have been purified and shipped. The pilot plant has an annual production capacity of 25 metric tons. The next step being planned is for a "Commercial 1" production facility that will produce 1,000 m.t./yr.

Sophorolipid has been shown to be an effective surfactant that has no toxicity and is completely biodegradable. The surfactant could be an alternative to petroleum-derived surfactants used in homecare and cosmetics products.

CYBERSECURITY GUIDANCE

Last month, the International Society of Automation (ISA; Research Triangle Park, N.C.; www.isa.org) Global Cybersecurity Alliance (ISAGCA), along with admeritia GmbH (Langenfld, Germany; www.admeritia.de), released the Top 20 Secure PLC Coding Practices document. The document, which can be downloaded at www.plc-security.com, aims to provide a list of coding practices for programable logic controler (PLC) programmers that have benefits for the information technology (IT) security of PLCs and the plants they control.

This public-sourced document utilized ISA members and leaders, many of whom have volunteered their time, to join forces with other colleagues and experts from around the world to help develop this grassroots list. ❐

New AI tool allows predictive maintenance on heat transfer fluids

A new predictive analytics tool for heat-transfer-fluid (HTF) life expectancy uses artificial intelligence (AI) algorithms built around HTF sample analysis data. The tool, known as Fluid Genius, is designed to provide recommendations for extending fluid life and maintaining HTF systems. Developed by Eastman Chemical Co. (Kingsport, Tenn.; eastman.com), Fluid Genius has been validated at both Eastman sites, as well as external user facilities.

"Engineers don't necessarily receive extensive information about heat transfer fluids in their undergraduate training, so many people working in plants need more information on how HTF systems operate on a day-to-day basis," explains Mark Brucks, segment marketing manager for HTFs at Eastman. "The AI-enabled Fluid Genius tool combines theoretical information with real-world experiential data to fill in the knowledge gaps for those working with HTFs."

Fluid Genius generates a fluid condition score, a unique measure of the overall fluid condition, as well as notifications about fluid trends and customized recommendations for proactive maintenance actions. These could include system venting, inert-gas blanket system installation and inspection, fluid replacement, the implementation of side-stream filtration and alerts for possible contamination, says Sharon Dunn, Eastman global commercial director for heat transfer fluids.

"Eastman has long-term technical experience in this area, along with decades-worth of sample analysis data on HTFs," adds Dunn. "We have leveraged those in our algorithms, which can provide specific recommendations for how to extend the performance of the HTF until the next scheduled shutdown."

Fluid Genius is accompanied by an easy-to-use, complimentary sampling kit. It has been deployed at a number of operating sites to date.

Extraction of plant products with supercritical glycerin

Construction is underway of a prototype system designed to extract natural product compounds from plants using supercritical glycerin as the extraction solvent. The initial target for the process is to extract cannabidiol (CBD) and tetrahydrocannabinol (THC) from *Cannabis sativa* plants.

"Most processes using supercritical fluids — such as carbon dioxide — to extract plant products end up with highly viscous products that are difficult to work with," explains inventor Demetri Hopkins. "The glycerin concentrates generated from this system can be used directly in a range of products, and allow standardized concentrations of the target compounds."

The intellectual property behind Hopkins' glycerin extraction technology has been licensed to incubator platform ECO Innovation Group Inc. (Van Nuys, Calif.; www.ecoig.com), and the prototype is being fabricated by high-pressure equipment specialist Fluitron Inc. (Ivyland, Pa.; www.fluitron.com).

While glycerin (propane-1,2,3-triol) is used as the supercritical extraction solvent, the process depends on a set of proprietary co-factors required to maintain glycerin in a supercritical state, and that promote the efficient dissolution of the desired molecules. In the system, the cofactors are separated from the products after the extraction step and recycled back to the process.

"The technology is amenable to automation, and allows users to standardize the product extraction and obtain consistent concentrations across different batches," Hopkins says, "which are features not present in the *Cannabis* market to date." Although *Cannabis* products, including vaping pens, are among the first planned by the team, the supercritical glycerin extraction technology can be applied to other end markets as well, including pharmaceuticals, herbal supplements, cosmetics, beverages and others. ■

Business News

Plant Watch

Huntsman to increase ethylene carbonate production capacity

June 14, 2021 — The Performance Products division of Huntsman Corp. (The Woodlands, Tex.; www.huntsman.com) is planning to significantly increase existing production capacity for ethylene carbonate at its Conroe, Texas facility by mid-2023. Ethylene carbonate is a component of lithium-ion batteries.

LyondellBasell announces startup of Ulsan PP production facility

June 10, 2021 — LyondellBasell Industries, N.V. (Rotterdam, the Netherlands; www.lyondellbasell.com) announced the startup of Ulsan PP Co.'s polypropylene (PP) production facility. The facility, located in Ulsan, South Korea, is designed to produce 400,000 metric tons per year (m.t./yr) of PP. Ulsan PP Co. is a joint venture (JV) between PolyMirae Co. (a 50-50 partnership of LyondellBasell and DL Chemical) and SK Advanced.

Air Products to build world-scale 'blue-hydrogen' plant in Edmonton, Canada

June 9, 2021 — Air Products (Lehigh Valley, Pa.; www.airproducts.com) plans to build a $1-billion "blue" hydrogen production and liquefaction facility in Edmonton, Alta., Canada. The new complex is expected to come onstream in 2024 and is envisioned to reach over 1,500 m.t./d of hydrogen production and achieve greater than 3 million m.t./yr of CO_2 capture.

Dow to build MDI distillation and prepolymers facility in Freeport, Texas

June 9, 2021 — Dow, Inc. (Midland, Mich.; www.dow.com) announced plans to build an integrated methylene diphenyl diisocyanate (MDI) distillation and prepolymers facility at its world-scale manufacturing complex in Freeport, Texas. The new Freeport MDI facility will be capable of supplying a 30% higher volume of MDI products.

Ascend expands production capacity for long-chain polyamides

June 9, 2021 — Ascend Performance Materials LLC (Houston; www.ascendmaterials.com) expanded production capacity for long-chain polyamides (PA 610 and PA 612) at its plant in Greenwood, South Carolina. These polyamides are used in photovoltaic supports, battery seals, brush bristles and many other applications.

Entegris invests $30 million to expand four U.S. manufacturing facilities

June 8, 2021 — Entegris, Inc. (Billerica, Ma.; www.entegris.com) will expand its manufacturing plants located in Billerica, Ma., Bloomington, Minn. and Logan, Utah. The expansions are part of Entegris' plan to invest $30 million in its Life Sciences operations in 2021. The expanded facilities will develop and manufacture bioprocessing assemblies.

Arkema to raise global production capabilities for fluorospecialty product

June 8, 2021 — Arkema S.A. (Colombes, France; www.arkema.com) finalized an agreement with Chinese producer Aofan to manufacture the fluorospecialty product 1233zd in China. At the same time, Arkema will accelerate the addition of 1233zd capacity at its Calvert City, Kentucky site. Aofan's initial capacity of 5,000 m.t./yr is expected to be commissioned in mid- 2022. The $60-million Calvert City expansion will add 15,000 m.t./yr of capacity and is expected to start up in late 2023.

Brightmark to build $680-million advanced-recycling plant in Georgia

June 8, 2021 — Brightmark LLC (San Francisco, Calif.; www.brightmark.com) will build the world's largest advanced plastics-recycling facility in Macon-Bibb County, Georgia. The total investment is expected to be more than $680 million for the new plant, which will convert 400,000 m.t./yr of plastic waste into 64 million gal/yr of ultra-low-sulfur diesel fuel and naphtha blendstocks and 20 million gal/yr of wax.

Perstorp to expand production capacity for 2-ethylhexanoic acid

June 2, 2021 — Perstorp AB (Malmö, Sweden; www.perstorp.com) will substantially expand its production capacity of 2-ethylhexanoic acid (2-EHA) beginning in 2022. 2-EHA is widely used in esters for film plasticizers and synthetic lubricants.

Wacker begins construction on new liquid-resins plant in Germany

June 2, 2021 — Wacker Chemie AG (Munich, Germany; www.wacker.com) started to build a new liquid-resins unit at its Nünchritz, Germany site. This unit will supply key upstream products for formulating silicone-based protection agents and binders for paints and industrial coatings. Scheduled to go onstream at the end of 2022, the company will invest around €30 million in the unit.

Eastman to expand capacity for cellulosic filaments at Barcelona site

May 27, 2021 — Eastman Chemical Co. (Kingsport, Tenn.; www.eastman.com) is increasing its production capacity for Naia cellulosic filament yarn at its Barcelona, Spain site. Capacity will increase by 30% in mid-2021, and by more than 50% by the end of 2022.

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Mergers & Acquisitions

Clariant to divest pigments business

June 14, 2021 — Clariant AG (Muttenz, Switzerland; www.clariant.com) has reached definitive agreements for the divestment of its pigments business to a consortium of Heubach Group and SK Capital Partners at an enterprise value of around $900 million to $950 million. The combined business will be a global pigments player generating more than €900 million in annual sales.

Kuraray to divest Calgon Carbon's UV water-treatment operations to De Nora

June 11, 2021 — Kuraray Co. (Tokyo, Japan; www.kuraray.co.jp) has announced plans to divest operations related to ultraviolet (UV) water-treatment and ballast water treatment run by its wholly owned subsidiary Calgon Carbon Corp. The divested operations will be transferred to De Nora Water Technologies, LLC (Milan, Italy; www.denora.com).

Equinor to sell petroleum refining business in Denmark

June 10, 2021 — Equinor Energy ASA (Stavanger, Norway; www.equinor.com) entered into an agreement with the Klesch Group for the sale of its petroleum refining business in Denmark. The agreement covers the Equinor Refining Denmark A/S company, which consists of the Kalundborg refinery and terminal in the northwest of Zealand, the Hedehusene terminal near Copenhagen and associated infrastructure and industrial properties. The Kalundborg refinery has a production capacity of up to 5.5 million m.t./yr of oil products.

Eastman to sell rubber additives assets for $800 million

June 10, 2021 — Eastman Chemical entered into a definitive agreement with an affiliate of One Rock Capital Partners, LLC to sell its rubber additives (including Crystex insoluble sulfur and Santoflex antidegradants) and other product lines and related assets and technology of the global tire additives business of its Additives & Functional Products segment. The total sale price is $800 million. The sale is expected to be completed in the second half of 2021.

Cargill and HELM establish renewable BDO joint venture

June 8, 2021 — Cargill, Inc. (Minneapolis, Minn.; www.cargill.com) and chemical marketing company HELM AG (Hamburg, Germany; www.helmag.com) are entering into a JV agreement under which the companies are investing a combined $300 million to build the first commercial-scale, renewable 1,4-butanediol (BDO) facility in the U.S. The new facility will be located at Cargill's existing biotechnology campus and corn-refining operation in Eddyville, Iowa. The plant is expected to be completed and begin operating in 2024.

POET acquires Flint Hills Resources' biofuel business

June 3, 2021 — POET, LLC (Sioux Falls, S.D.; www.poet.com) has acquired the bioethanol assets of Flint Hills Resources, LLC (Wichita, Kan.; www.fhr.com) in their entirety. This transaction expands POET's production capacity by 40%. The acquisition includes six bioprocessing facilities located in Iowa and Nebraska and two terminals in Texas and Georgia.

BASF concludes sale of production plant in Kankakee, Illinois

June 2, 2021 — BASF SE (Ludwigshafen, Germany; www.basf.com) concluded the sale of its manufacturing site in Kankakee, Ill. to an affiliate of private equity firm One Rock Capital Partners, LLC. The agreement also includes the associated businesses of vegetable-oil-based raw-material sterols and vitamin E, anionic surfactants and esters produced at the Kankakee site.

Saint-Gobain divests two glass-processing plants in Germany

June 1, 2021 — Saint-Gobain S.A. (Paris, France; www.saint-gobain.com) announced the sale of Saint-Gobain Glassolutions Objekt-Center, which specializes in glass processing as part of the Glassolutions network in Germany. This sale to Munich-based Aequita group involves sites in Döring Berlin and Radeburg. Aequita purchased Glassolutions' Netherlands operations in 2019.

Lummus partners with Synthos on bio-based butadiene technology

June 1, 2021 — Lummus Technology, Inc. (Houston; www.lummustechnology.com) and Synthos S.A. (Oswiecim, Poland; www.synthos.com) are collaborating to commercialize Synthos' bio-based butadiene technology. The partners will develop a feasibility study for a 20,000-m.t./yr bio-based butadiene plant.

Shell sells stake in Deer Park Refinery to Pemex for $596 million

May 26, 2021 — Shell Oil Co., a subsidiary of Royal Dutch Shell plc (The Hague, the Netherlands; www.shell.com), has reached an agreement for the sale of its interest in Deer Park Refining Ltd. Partnership, a 50-50 JV between Shell Oil and a subsidiary of Petroleos Mexicanos (Pemex; Mexico City; www.pemex.com). The transaction will transfer full ownership of the refinery to Pemex for a total consideration of $596 million. The refinery has a crude-oil capacity of 340,000 barrels per day, processing oil from Mexico, Canada, the U.S., Africa and South America. ■

Mary Page Bailey

Temperature Measurement Gets Smarter and Safer

New innovations in temperature sensors, calibration and associated equipment are helping to keep plants operating reliably and safely

Temperature is one of the most important process parameters that needs to be measured and controlled in the chemical process industries (CPI). For this reason, vendors are continuously improving temperature sensors, transmitters and the associated hardware and software to ensure accurate and reliable measurements, while ensuring safety at the plant. And despite the analog nature of traditional thermocouples and resistance-temperature detectors (RTDs), digitalization is now "par for the course," while the industrial internet of things (IIoT) and Industry 4.0 trends go hand-in-hand with making the process and the process equipment more reliable.

"The major trends in temperature measurement these last few years have revolved around safety, digital transformation and innovation," says Kevin Stultz, global product manager for Emerson's Rosemount Temperature (St. Louis, Mo.; www.emerson.com). "New software and digital tools are becoming more prevalent in the industry, as customers want more data on their process and faster service, this leads to a demand for reducing complexity and improving speed of innovation," he says.

Advances in calibration

Although the characteristics and operation of traditional thermocouples and RTDs are well understood, they still need to be calibrated — not just the first time after the sensor is made, but at regular intervals to account for aging, which can lead to drift. In some CPI sectors, such as pharmaceuticals, food and beverages and life sciences, calibration at regular time intervals is both standard and required by regulation. Because the sensor normally needs to be removed from the process to be calibrated, the procedure is both disruptive and time consuming.

FIGURE 1. The Beamex MC6-T automated temperature calibration system is shown here being used in the field

"Today, with IIoT, we get the calibration data in digital format — every number is recorded, so you can do some cool analytics," says Ned Espy, technical director at Beamex, Inc. (Marietta, Ga.; www.beamex.com). You can compare a temperature probe over time, or compare different probes with each other over time, explains Espy. With this information, you might find that you can extend the time interval between calibrations, he says.

There is a growing awareness for data integrity issues and minimizing human errors, Espy continues. "The calibration data are recorded as observed, so there is no human error. Our system has a high level of automation, so users can get away from using paper," he says.

Introduced in 2019, the Beamex MC6-T (Figure 1) is a portable, automated temperature-calibration system that combines a state-of-the-art temperature dry-block with the Beamex MC6 multifunction process calibrator technology. With the ability to generate temperature, as well as measure and simulate temperature and electrical signals, it offers a unique combination of functionality, says Espy. MC6-T is a documenting calibrator and communicates with calibration software. This enables a digitalized and fully paperless calibration process.

An alternative calibration approach is evolving at Endress+Hauser Temperature+System Products (Nesselwang, Germany; www.ehts.endress.com) — self calibration. In 2017, after seven years of development, the company introduced the iTHERM TrustSens TM371 (Figure 2) — the world's first self-calibrating temperature sensor.

According to Endress+Hauser, the iTHERM TrustSens integrates a high-precision reference with long-term stability into the temperature sensor itself. The reference material has a unique and fixed point, its Curie point (T_C), which is the temperature where the ferromagentic properties of the material abruptly change. This change in properties can be detected electronically, which in turn enables the point at which T_C is reached to be determined and used as the reference temperature for calibrating the Pt100 sensor.

The exact T_C for the reference

FIGURE 2. The iTHERM TrustSens uses an internal reference material that enables the device to recalibrate itself without removing the sensor

material is determined with extreme accuracy for each sensor (typically around 118.0°C), so each time there is a cooling process starting at higher temperatures, such as a steam-sterilization of the plant, the sensor is calibrated automatically. If the measured deviation between the reference and the sensor is outside the set limits, the device sends an alarm message, which is also displayed on the device as a flashing red LED.

Because steam-sterilization is often performed daily, the calibration is performed much more frequently compared to manual calibration intervals that have been determined based on a risk assessment. This saves considerable time and money, because the calibration is performed without any personnel costs or additional planned downtimes, says marketing manager Amar Löffler.

Although it took some time to convince users, the TrustSens is now becoming accepted by industry, with thousands of units installed, says Löffler. From initial field testing, it was found that the device doesn't just save time, but it prevents mistakes — "improved precision (that is, consistency of accurate results at lower risk of drift or undetected failures) was found to be the biggest benefit," he says.

Endress+Hauser is further developing this technology for applications in the chemical industry, where clean-in-place operations are performed regularly, but at lower temperatures, says Löffler. The company has been looking for a reference material with a T_C of around 60°C for such applications.

Thermowell design

Last June, Emerson introduced the Rosemount Thermowell Design Accelerator (TDA), which eliminates the largest "pain point" of temperature process design — manual thermowell iterations — significantly increasing operational efficiencies and cost savings. "Emerson's TDA allows customers to perform wake frequency calculations per ASME PTC 19.3 on their thermowell designs, and automatically iterates failed tags to reduce design time," explains Emerson's Stultz. The TDA software will also provide users with solutions, including Rosemount X-well Technology (described below) and Rosemount Twisted Square thermowell.

When conventional thermowells don't pass the ASME PTC 19.3 thermowell evaluations, the majority of the time it is due to dynamic stress on the thermowell from the process, explains Stultz. "The Rosemount Twisted Square thermowell design [Figure 3] eliminates over 90% of these dynamic stresses to achieve an accurate process temperature measurement and reduce the risk of thermowell failure," he says. "This leads to a more accurate, safer temperature measurement."

Last year, Endress+Hauser introduced a patented Dual Seal feature for its iTHERM Moduline TM131 temperature transmitter, which adds a second safety barrier to the process. The loss of thermowell integrity, due to abrasion or corrosion, is detected and immediately seals off the sensor insert, thereby preventing the leakage of hazardous process medium to the environment or into the control room (for example, through conduits). The temperature transmitter then relays a message to the control system so that safety measures can be taken to avoid harm to people or the environment, explains Löffler. "In the past, it could take a long time before you realize there a problem, and might only notice after the damage is done," says Löffler.

Non-invasive measurement

"The biggest trend and technological development we see at Measurement & Analytics is clearly non-invasive temperature measurement," says Guruprasad Sosale, global product manager, non-invasive & wireless technologies of ABB Measurement & Analytics (Munich, Germany; www.abb.com). "In 2018, ABB ushered in a new era of temperature measurement, using non-invasive sensors, when we launched our very own non-invasive sensing device that allows plant operators to measure process temperature without compromising on performance: no shutdown, no holes, with dramatically simplified engineering," he says.

"Every plant process engineer, maintenance engineer and plant manager knows the benefit of being able to measure temperature accurately without having to engineer and install a thermowell. For future facilities, a non-invasive approach to temperature measurement simplifies engineering temperature points and dramatically reduces the capital expenditure costs of up to 75% due to reductions in design and engineering, materials and installation costs," says Sosale.

To measure surface temperatures, ABB uses a double sensor architecture that overcomes the drawbacks of traditional skin-temperature sensors, explains Sosale. One sensor is in contact with the surface of the pipe while the second measures the ambient temperature in the vicinity. A thermal model using these measurements compensates for contact resistances and ambient effects to measure the surface temperature at the tip. The actual process temperature is then inferred using thermal models of typical fluids flowing in piping to predict

FIGURE 3. The Rosemount Twisted Square thermowell design reduces the risk of thermowell failure

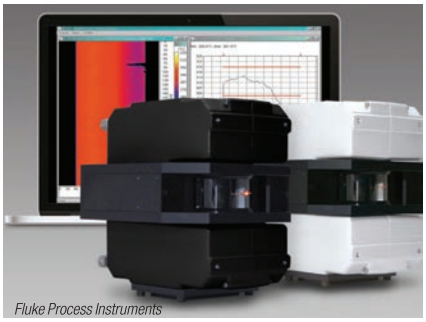


FIGURE 4. This new Linescanner measures over a thousand temperature points along a scan line in 300 seconds

the temperature fields under common process conditions. "...for the majority of liquid- and steam-measurement applications, ABB's new non-invasive sensors are just as accurate and responsive as those placed in thermowells," says Sosale.

Emerson has also developed non-invasive temperature measuring devices. The Rosemount X-well Technology calculates an accurate process temperature without the need for a thermowell or any process penetrations by using a thermal conductivity algorithm, says Emerson's Stultz. "This innovative design allows for a simpler, safer and more cost-effective temperature measurement solution for the customer."

Multi-point measurement

"One of the trends we are seeing is that customers want more measurement capabilities than just a spot pyrometer, which only provides a single point of data," says Jeff Kresch, product manager, Infrared Products at Fluke Process Instruments (Everett, Wash.; www.flukeprocessinstruments.com). "Operators are looking for more temperature information about their process, alluding to the fact they'd like to look at an area of measurement or multiple points of measurement at once," he says.

"What we're currently seeing across many of our applications is, where 10 years ago we would have sold pyrometers, we're now selling fixed thermal imagers," Kresch continues. "So thermal imaging is bleeding into the pyrometry measurement area."

New technologies revolve around using vision and infrared (IR) simultaneously, continues Kresch. "Being able to see the process visually, but also from a thermal-temperature-measurement standpoint, is new, and I think that's one of the key things that operators are looking for," he says. "We've been introducing more high-end technologies for making area measurements and recording data — including a number of changes to our thermal-imaging product line, particularly for looking at tanks, vessels and gasification systems in the chemicals industry."

Last April, the company introduced the MP Linescanner Series (Figure 4), which delivers continuous, accurate, edge-to-edge thermal images and temperature measurements for high-speed manufacturing processes. The device delivers real-time imaging at scan speeds up to 300 Hz. Such high speeds are necessary for detecting temperature abnormalities, such as hot spots. The new Linescanners can measure up to 1,024 temperature points across a scan line at a rate of 300 lines per second, the company says.

The company also offers customized process-imaging systems to meet the specific application requirements for processes like glass processing, extrusion coating, thermoforming machine control, kiln shell monitoring and gypsum wallboard production. Fluke Process Instruments is also getting ready to introduce a new ATEX-certified model of the Thermalert 4.0 Pyrometer, which can survive in explosion-proof environments.

While not brand new, fiber optics technology is gaining increasing interest as a solution for multi-point temperature measurements, says Nicholas Meyer, product marketing manager at Yokogawa Corporation of America (Sugar Land, Tex.; www.yokogawa.com/us). A single fiber optic cable is capable of monitoring thousands of temperature points, making it an attractive solution for large-scale applications, such as tanks and pipelines, he says. "Fiber-optic temperature solutions, such as Yokogawa's DTSX, can be used to detect leaks in vessels or pipelines, improving operational safety and reducing potential environmental impact."

Meanwhile, for multipoint tempera-

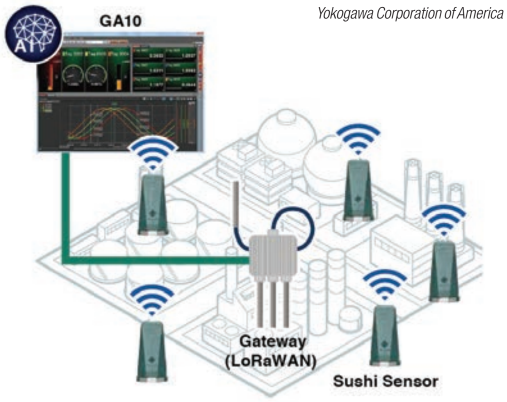


FIGURE 5. Yokogawa's Sushi Sensors wirelessly monitor temperature, pressure and vibrations of process equipment throughout a plant

ture measuring, Endress+Hauser offers iTHERM ProfilsSens TS901, a patented multipoint sensor cable developed for the petroleum refining industry. It accurately measures temperature profiles in catalytic hydroprocessing units, such as hydrotreaters, hydrodesulfurization and hydrocracker units. "This very new technology has undergone a long period of field testing, and has now been used in several hydrotreating units where the conditions are very harsh (250–480°C or higher, and pressures of 200 bars)," says Löffler. The flexible probe is said to drastically reduce process perturbation due to its minimally invasive design.

Monitoring equipment

Reliable temperature measurement is not only important for controlling a process, but also for monitoring the health of equipment surrounding the process. IIoT has been a strong trend influencing instrumentation and especially temperature technology, says Gerald Hardesty, product marketing manager at Yokogawa. The ease with which you can install a new wireless temperature transmitter has also created a pull for non-intrusive sensors, he says. "This allows for ultimate flexibility with obtaining new temperature measurements. These new measurements are not directly related to process control, but are used to help improve reliability and efficiency."

"New temperature measurements can also be combined with other data to assess the health and performance of operational assets," continues Hardesty. "With Yokogawa's Sushi Sensors (Figure 5), the temperature measurements can be taken as surface temperatures (non-intrusive) via a magnetic mount or screw mount sensor, or from the process via thermocouples connected to a wireless sensor." For example, such technology can be used to identify failed stages in multistage heat exchangers, monitor energy loss due to steam leakage, and temperature monitoring of tanks and firebricks, says Meyer. "Finally, the data can be collected and analyzed on premise, taken to the Cloud, or both." ■

Gerald Ondrey

Pipes, Tubes & Fittings

Reduce costs for purging large-diameter pipes

Care is necessary when welding large-diameter pipework in stainless, duplex and chrome steels, nickel alloys and zirconium. When welding such reactive materials, they need to be purged of oxygen before, during and after welding, which can cause a huge expense when they are of a large diameter. QuickPurge Systems (photo), which are manufactured in sizes up to 88 in. (2,235 mm), dramatically reduce the space that needs to be purged, thereby reducing purging time dramatically, resulting in savings in both time and gas costs, says the company. QuickPurge is simply inserted into a tube or pipe, inflated within the pipe, restricting the area that is to be welded, reducing the O_2 level down to 100 parts per million (ppm) within minutes. QuickPurge has an additional gas input line, which means that extra purge gas can be introduced for applications such as this, thereby achieving a much faster purge, down to the lowest oxygen levels, which is perfect for larger-diameter pipes where quality welds are required. — *Huntingdon Fusion Techniques HFT, Burry Port, Carms, U.K.*
www.huntingdonfusion.com

Huntingdon Fusion Techniques HFT

Manage flanges with these tags

Leaks caused by improperly sealed flanges connecting pipes, valves, pumps and other equipment to form piping systems may cause corrosive damage. Such damage is both expensive and time-consuming to repair, and puts both workers and others at risk of exposure to dangerous pipe contents. Using this new family of tough multi-colored flange-management tags gives inspectors and field workers peace of mind knowing that the work has been done accurately, on time and by professionals in the field. The tags are made from polypropylene, so they are durable, and resistant to water, tearing and ultraviolet (UV) light. Highly visible "at-a-glance" status signifies each stage of inspection — flange assembled, flange tightened, flange broken and inspected. Each stage is perforated and can be torn off to show completion. An 8-mm hole at the head of the tag enables the tag to be easily attached to the flange using cable ties. All tags can be customized to include company logo and sequential numbering for traceability with orders above 500 units. — *Tuffa Products, Chicago, Ill.*
www.flangetags.com

Recycling silicone tubing waste into silicone oil

This plastic- and silicone-tubing manufacturer is now able to recycle the waste from its silicone tubing and braid-reinforced hose extrusion processes (photo). The recycled scrap finds new life as silicone oil for industrial applications. Tubing scrap is created at the beginning and end of the extrusion process as technicians adjust the equipment for proper tubing dimensions. That tubing, and any other that does not meet the company's strict quality standards, is collected and stored in bulk containers. The containers are then shipped to ECO USA, a company that specializes in reclaiming silicone oil. At ECO USA's silicone recycling plant in Parkersburg, West Virginia, silicone is ground into small pieces, mixed with catalysts and heated to break down its chemical bonds. Liquids from this stage are filtered, refined and polymerized into silicone oils and filtered again. The final product is silicone oil that is comparable to virgin silicone oil manufactured from silicon dioxide. The oil is used in industrial applications, such as lubricants, sealants and automotive dressing. — *NewAge Industries, Inc., Southampton, Pa.*
www.newageindustries.com

NewAge Industries

This new piping system handles aggressive media

This company has added SYGEF ECTFE (photo) to its extensive line of engineered piping systems. The new SYGEF ECTFE product was designed specifically to con-

GF Piping Systems

Smart Hose Technologies


Gericke USA

Zetec

vey highly aggressive media, such as concentrated sulfuric acid and hydrogen peroxide, without corrosion, even under extreme pressure and temperature conditions. Made of ethylene-chlorotrifluoroethylene, the SYGEF ECTFE system is said to offer excellent physical properties. The high-performance fluoropolymer material allows use in a broad temperature range from –105 to 284°F (–76 to 140°C), and with aggressive chemicals approved between 32 and 176°F. SYGEF ECTFE is available in pipe, valves and fittings from 1/2 to 4 in., and features quick assembly, long service life and lower initial costs than welded PFA (perfluoroalkoxy alkane) systems. Also when compared to PFA, SYGEF ECTFE has a 200% higher pressure range and 20% more efficiency in pipe volume, says the manufacturer. — *GF Piping Systems, Irving, Calif.*
www.gfps.com

Hose assemblies for extreme pressure

The Extreme Pressure polytetrafluoroethylene (PTFE) hose assembly (photo) is designed to work with extreme-pressure PTFE hoses. It utilizes an internal cable that is designed specifically for extreme-pressure PTFE gas applications. When a high-pressure cylinder-filling hose assembly fails, the hose can whip violently, resulting in property damage, personnel injury and even death. The Smart-Hose Safety System can protect facilities and workforce from the potentially devastating consequences associated with high-pressure hose failures. Integrated valves will instantly stop product flow if a catastrophic failure occurs. No human intervention is needed to activate. The tube is gas quality or heavy wall smooth-bore virgin PTFE tube reinforced with two aramid Braids and one high-tensile 304 maypole-wound stainless-steel braid. The operating temperature ranges from –54 to 150°C. — *Smart Hose Technologies, Folcroft, Pa.*
www.smarthose.com

A new line of pneumatic conveying elbows

The Bend line of elbows (photo) was developed to protect particle shape, reduce elbow wear and save space in pneumatic conveying systems. These elbows replace conventional-sweep and long-radius elbows with a compact design configuration that gathers material and conveying air or gas in a round, rotating deflection zone that virtually eliminates destructive particle impact with the elbow wall. With the gradual, gentle release of the material downstream, the pipe elbows promote smooth, efficient conveying and a dust-free environment with reduced line downtime, resulting in substantial savings in maintenance. Proven effective for conveying abrasive, heat-sensitive and other powders, pellets, flakes and slurries, the Bend line of vortex elbows is available in seven different sizes to suit a wide range of material properties and throughput requirements. The 90-deg tube elbows are offered in cast iron or optional stainless steel with a variety of coatings to suit the conveyed materials. — *Gericke USA, Inc., Somerset, N.J.*
www.gerickegroup.com

Perform examinations of pipe elbows with this scanner

The ElbowFlex scanner (photo) enables quick, manual ultrasonic inspections of pipe elbows in oil-and-gas, petrochemical and other industrial applications. ElbowFlex measures wall thickness and detects flow-accelerated corrosion on elbows with diameters ranging from 4 in. NPS (4.5 in.) to flat. Its 1-D flexible, linear-array probe can adapt to the scanned specimen dimension and stay concentric throughout the inspection, providing everything needed to cover the full range of elbow diameters in a single probe. It is able to scan both the straight and elbow aspects of a pipe. ElbowFlex uses an Aqualene membrane for coupling in lieu of a water chamber and requires only a thin film of water on the specimen surface. The scanner can also work with standard coupling gel or a mixture of water and gel. The complete ElbowFlex kit includes the scanner, flexible probe, Aqualene membrane, encoder cable, wear shoes, shims, tools, carrying case and spare components for consumables. — *Zetec Inc., Snoqualmie, Wash.*
www.zetec.com ■

Gerald Ondrey

New Products

This ultrasonic flowmeter can be installed almost anywhere

Many process plants have difficulty finding ideal installation points for flow-measurement devices due to requirements for long length of inlet run and undisturbed flows. The Prosonic Flow P 500 (photo) addresses these and other issues with its FlowDC function. The device requires only minimal straight inlet runs and it can be installed directly onto the exterior of the pipe, so there is no need to interrupt operations. The Prosonic Flow P 500 can be installed in nearly any location, independent of the pipeline design. Prosonic Flow P 500 provides measurement for a wide variety of fluids, such as chemicals, liquid hydrocarbons, solvents, acids, bases, water and many others. It can be mounted on a wide variety of pipeline types and materials: on metal pipes made of steel or cast iron; plastic pipes; glass-reinforced plastic pipes; and pipes made of composite materials — all with or without lining. A special, maintenance-free contact foil (coupling pad) provides optimal sound transmission between the sensor surface and the pipe. — *Endress+Hauser, Greenwood, Ind.*

www.us.endress.com

Endress+Hauser

Software optimizes usage of full-containment storage tanks

This company has enhanced its Rosemount TankMaster inventory-management software package (photo) to help optimize tank usage and increase safety in full-containment storage tanks for liquefied natural gas (LNG) and other liquefied gases. These tanks are large, complex structures with a typical capacity of up to 200,000 m^3, which places specific demands on tank-gauging systems. By providing both inventory management and roll-over prediction in a single software solution, TankMaster reduces both cost and risk, says the company. Roll-overs are dangerous releases of boil-off vapor that can occur when LNG stratification is left unchecked. The consequences can be severe — including extensive tank damage and the release of large quantities of LNG into the atmosphere. TankMaster software uses data from level, temperature and density measurement devices incorporated into the Rosemount Tank Gauging System to calculate when a roll-over might occur, enabling operators to take preventative action. — *Emerson, St. Louis, Mo.*

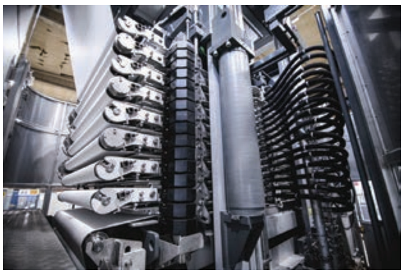
www.emerson.com

Emerson

Improve performance with these filtration inspection packages

This company recently launched three filtration inspection packages (photo) centered around offering improved filter availability, better filter performance and longer equipment life. The packages are designed to quickly identify common wear-and-tear issues, such as problems with the plate packs, leakages and misalignments, among others. Filtration inspections have the advantage of not only discovering issues that require immediate attention, but also allow for the identification of possible upcoming larger filtration failures or upgrade opportunities. It makes it possible to proactively respond to, and put in place a service plan to address longer-term problems. This has the potential to save users significant costs in terms of lost production, says the company. — *Metso Outotec Oyj, Helsinki, Finland*

www.mogroup.com



Metso Outec

This safety instrumented system has cybersecurity protection

The ProSafe-RS safety instrumented system (SIS; photo), a product in the OpreX family, recently obtained ISASecure CSA Level 1 certification from the ISA Security Compliance Institute (ISCI). This is the first time a safety instrumented system has obtained this cybersecurity certification, says the manufacturer. Receipt of this certification indicates that a product has been recognized by a third party as having security controls that conform to international standards for control-device security. The ProSafe-RS safety instrumented system is certified for use in safety integrity level 3 (SIL 3) applications. This company also plans to obtain ISASecure CSA certification for the ProSafe-RS Lite SIL 2 SIS, which was released in January. — *Yokogawa Corp. of America, Sugar Land, Tex.*

wwww.yokogawa.com/us

Yokogawa Corp. of America

Goudsmit Magnetic Systems

Labom Mess- und Regeltechnik

Büchi Labortechnik

Dinnissen

Separate metal particles from powders and granulates

This company recently launched a rotating Cleanflow magnetic separator (photo) suitable for installation in free-fall lines in a continuous process. Cleaning takes place without stopping the product flow. During the cleaning cycle, the magnets stay in the product flow. This guarantees the user that no iron falls back into the product during cleaning, something that was regularly a problem with other systems. The unit can be used in the chemical, ceramic, plastic and recycling industries, among others. In the latter case, it is used to make plastic or rubber granules metal-free. The magnetic bars in the Cleanflow magnetic separator filter metal particles and paramagnetic particles from 30 µm out of powders and granular products. The separator is suitable for high-capacity product flows (up to approximately 60 m^3/h) and distinguishes itself by the very high magnetic flux density of over 9,000 Gauss at the contact surface of the bars. — *Goudsmit Magnetic Systems BV, Waalre, the Netherlands*
www.goudsmitmagnets.com

Optimized measuring devices for the pharmaceutical industry

The Pascal CV4 pressure transmitter (photo) has a high-resolution graphic display with backlighting. The device meets all typical requirements for pharmaceutical processing. Its high accuracy enables precise dosing in the filling process so that valuable product is not lost. The Pascal CV4 also meets strict hygiene requirements. It can be combined with a selection of easy-to-clean hygienic diaphragm seals in a variety of sizes and designs. These process connections protect against product loss and ensure that systems are easy to clean. Connections suitable for clean-in-place (CIP) and steam-in-place (SIP) make residue-free cleaning possible with designs that are free of dead spaces. In addition to this, the company offers the completely autoclavable mechanical pressure gage BH8 (photo) and the resistance thermometer GA2610 with clamp-on technology. — *Labom Mess- und Regeltechnik GmbH, Hude, Germany*
www.labom.com

This new industrial evaporator has many features

The Rotavapor R-250 Pro industrial evaporation unit (photo) now includes the capacity of a 50-L evaporation flask. The new system offers a unique operating concept, many safety features and a robust design to improve demanding workflows in large-scale rotary evaporation. Conveniently, the interface from the benchtop Rotavapor R-300 to the industrial 20-L R-220 Pro and the new R-250 Pro remains the same, so scaling up is easy. This company's Open Interface and Cloud Services enable remote control and monitoring of the Rotavapor via a desktop computer, laptop or mobile device. Convenient push notifications with key process parameters, predictive maintenance, effortless firmware updates and data-logging options improve the user experience and minimize the risk of errors and downtime. Sensor technology, consisting of a foam sensor, a level sensor and a cooling temperature sensor, enable unattended distillations. — *Büchi Labortechnik AG, Flawil, Switzerland*
www.buchi.com

This new bag emptier has a body that tilts

The tiltable Dima bag emptier (photo) can improve product intake processes, since less time is needed to clean, inspect or replace parts. The tiltable body enables the Dima to be opened for easy access to areas that are normally difficult to reach. This speeds up cleaning, inspection and part replacements. Opening can be done by a single operator, simply by turning a handwheel. Air ventilation ensures that no dust will escape. — *Dinnissen B.V., Sevenum, the Netherlands*
www.dinnissen.nl

Barcode scanner for use in hazardous areas

The IS-TH1 (photo) is said to be the first handheld barcode scanner for use in hazardous areas and other industrial environments. The new device incorporates scanning technology from Zebra, and has been developed for two ranges. A mid-range variant scans up to 6 m and an extended-range variant scans over 15 m. Data

capture uses Zebra's reliable imager-scan engines, which offer unmatched decoding times and advanced barcode-processing capabilities. The IS-TH1 becomes a multi-function mobile device when combined with the company's IS530.x smartphone. To use the handheld barcode scanner, it must be connected to the smartphone and, through this connection, requires neither Bluetooth nor a separate battery. Power and data are generated by the IS530.x with 13-pin ISM interface (connection option for RSM, PTT headset, among others) as if via a mobile computer and processed at top speed. Thanks to the HID factory setting, the captured 1D/2D barcode is immediately recognized and processed as a keyboard input. — *i.safe Mobile GmbH, Lauda-Koenigshofen, Germany*
www.isafe-mobile.com

Measure density and concentration with this system

The InlineSENS (photo) density measuring system combines both a radiation source and scintillation detector in one device. Its use of low-energy gamma radiation provides strong responses to even the slightest change in product composition, with extremely low dose rates. The InlineSENS offers high statistical accuracy and long-term stability by using a highly sensitive scintillation detector with patented drift compensation. The measuring system, which is made entirely of stainless steel, is permanently flanged to the pipeline and continuously measures the product density of liquids, suspensions, slurries and bulk solids. Depending on the existing pipeline, various flange and product pipe options are available, including DIN flanges, ASA flanges and threaded connections between DN 40 and 65. — *Berthold Technologies GmbH & Co.KG, Bad Wildbad, Germany*
www.berthold.com

Use this flowmeter to monitor seal leakage in gas compressors

The ST75 mass flowmeter (photo) provides precision measurement in small lines for the detection of hazardous, non-compliant and costly gas leaks, including the monitoring of seal leakage from gas compressors. It measures air or gases from 0.01 to 559 std. ft^3/min depending on line size and actual process conditions. The ST75 is factory-calibrated and can provide a flow turndown range up to 100:1. With built-in temperature compensation, the ST75 offers highly repeatable performance in harsh industrial process environments. It features accuracy to ±2% of reading with ±0.5% repeatability over varying process temperatures and pressures in line sizes from 0.25 to 2 in. — *Fluid Components International LLC (FCI), San Marcos, Calif.*
www.fluidcomponents.com

This servo motor has ProfiNet with PROFIdrive integrated

This company's fully integrated ProfiNet motor solution has been officially certified by the Profibus user organization, an important milestone in terms of cabling, commissioning and IIoT capability. It is said to be the first drive-technology manufacturer to fully integrate its certified ProfiNet solution with PROFIdrive into a motor. Currently, the products BG 95 dPro (photo), BG 75 dPro, BG 66 dPro and the BGE 5510 dPro are available with ProfiNet interface, covering the output power from 1 to 4000 W. — *Dunkermotoren USA Inc., Mount Prospect, Ill.*
www.dunkermotoren.com

This touchscreen monitor is suitable for outdoor usage

The SRMHETRWP-15C (photo) is a rugged, industrial-grade 15-in. sunlight-readable touchscreen. This new model provides many important advantages for use in any automated outdoor system. With super-high visibility and brightness, this model is five to six times brighter than standard screens, making it suitable for use in direct sunlight. An automated sensor dims and brightens the screen based upon ambient light conditions. The monitor has a corrosion-resistant, waterproof stainless-steel enclosure that withstands rain, sleet and snow. It will operate in temperatures from –22 to 185°F. — *TRU-Vu Monitors, Inc., Arlington Heights, Ill.*
www.tru-vumonitors.com ■

Mary Page Bailey and Gerald Ondrey


i.safe Mobile


Berthold Technologies


Fluid Components International


Dunkermotoren USA


TRU-Vu Monitors

Adsorption bonding

Department Editor: Scott Jenkins

Physical adsorption phenomena play a critical role in many separation and purification processes, including separations of industrial gases, purification of gases, moisture removal from fluids, water purification and others. Adsorption is a surface phenomenon in which a fluid (gas or liquid) molecule attaches to the surface of a material by physical forces known as Van der Waals interactions. This one-page reference discusses the nature of Van der Waals forces, and their role in adsorption processes, with a focus on London dispersion forces.

Van der Waals forces

Van der Waals forces is a general term that describes the relatively weak (compared to typical covalent bond strengths) intermolecular forces that result from individual electrostatic attractions between otherwise non-attracting atoms and molecules. Van der Waals interactions can be classified into three categories, as follows:

Hydrogen bonds. Hydrogen bonds form between H atoms — that acquire significant positive charge from being bound to electronegative elements — and negatively charged lone electron pairs on adjacent molecules. The most important H-bonds form with hydroxide and amide groups. Hydrogen bonds have strengths ranging from 5 to 50 kJ/mol.

Dipole-dipole interactions. Dipole-dipole interactions are the attractive forces that arise when the partial positive and negative charges that form on polar molecules are attracted to each other. These permanent attractive forces act at close range.

London dispersion forces. London dispersion forces refer to the electrostatic attraction of spontaneously formed transient temporary dipoles that arise in non-polar molecules. For adsorption phenomena, London forces are the most important.

London forces

For a neutral molecule or atom, the average charge distribution is zero, but at any given instant, molecules have asymmetric distributions of electron density. Temporarily fluctuating dipole moments can arise from a brief shift of orbital electrons to one side of an atom or molecule. In adsorption, these transient dipoles induce complementary dipoles in neighboring molecules so that adsorbents are attracted to adsorbate molecules and they attach. These temporary induced dipoles are known as London dispersion forces, named for Fritz London, the German physicist and Duke University professor who described the intermolecular forces of noble gas atoms in 1930.

London forces have the following characteristics:

Non-chemical. London forces attract molecules to each other, but do not chemically change the molecules

Additive. The observed London force is the sum of all the individual interactions of the adsorbate molecule and the neighboring molecules. In adsorption onto activated carbon, for example, the magnitude of the London forces will be related to the density of carbon within the vicinity of the adsorbate molecules

Nonspecific. London forces are present among all molecules

Temperature-independent. London forces are unaffected by temperature, and thus the adsorption forces will be constant with temperature. Adsorption capacities will still be sensitive to the changes in vapor pressure or solubility of the adsorbing molecules that result from temperature differences

Short-ranged. The magnitude of the London force is sensitive to the proximity of the adsorbate molecules from the adsorbent material. London forces can be considered negligible at separations greater than about two molecular layers. In activated carbon, the adsorption forces are significant if the gaps or voids within the pores of the carbon structure (pore widths) are less than four or five molecular layers.

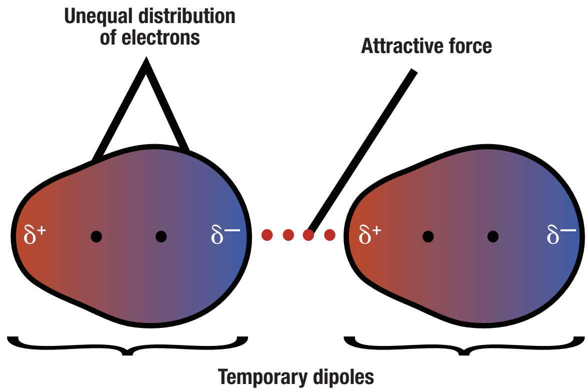


FIGURE 1. Transient dipoles resulting from spontaneous shifts in electron densities among molecules give rise to attractive forces

Bond strengths

Bonding energies in adsorption range from about 10 to 70 kJ/mol, much lower than typical covalent bond energies of 200 to 500 kJ/mol. The adsorption bonding energy is high enough for adsorption to occur, yet low enough to allow the adsorbent to be regenerated by removing the adsorbed molecules.

Adsorption

The affinity of a fluid component for a particular adsorbent depends on molecular characteristics, such as size, shape, and polarity of the adsorbent material, as well as the partial pressure or concentration in the fluid, and the system temperature.

Commercial adsorbents are highly porous, with pore surface areas ranging from about 100 to 1,200 m^2/g. The large surface area allows a large amount of adsorption relative to the weight of the adsorbent. A number of factors can affect adsorption, such as pore size distribution, molecular size of the impurity species, particle size of the adsorbent, pH of the solution and others. Activated carbon is one of the most complex solid adsorbents, and is very versatile because of its extremely high surface area and micropore volume. ■

Editor's note: Information for this column came from several sources, including: Clark, J., Intermolecular Bonding, article in Chemguide (www.chemguide.co.uk) 2017; Desotech, Carbonology articles: What is adsorption?, www.desotech.com, accessed June 2021; and others

Production of Caprolactam from Benzene

By Intratec Solutions

Caprolactam (Figure 1) is a cyclic amide widely used as a chemical intermediate. The main forms of caprolactam are molten (liquid) and flakes. At ambient temperatures, it is a white, hygroscopic, crystalline solid.

Almost all caprolactam is used as monomer in the production of polycaprolactam, also known as nylon 6. Fibers, sheets, filaments and bristles made from nylon 6 can be used, in turn, in a broad range of products, including apparel and home furnishings; carpets; and industrial uses (tires, reinforced rubber products).

The uses and applications of caprolactam may vary according to the product grade. Commercial caprolactam is produced with high purity, where water is usually the main contaminant with concentrations around 0.1 wt.%. Caprolactam can be used in the manufacture of other products, including 6-aminocaproic acid; caprolactam disulfide; hexamethyleneimine; polyamide 6 terpolymers; poly(ether-amide) elastomers; *n*-vinyl caprolactam and lysine.

The process

Caprolactam production involves four major sections: (1) benzene hydrogenation; (2) cyclohexane oxidation; (3) oximation & Beckmann rearrangement; and (4) ammonium sulfate purification (Figure 2).

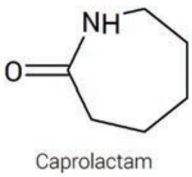


FIGURE 1. Caprolactam structure is shown here

Benzene hydrogenation. First, dried benzene is reacted with hydrogen in two steps, in the presence of platinum-based and zinc-oxide catalysts, to form cyclohexane. The intermediate is purified in two columns and hydrogen is recycled to the reactor.

Cyclohexane oxidation. The cyclohexane is converted to a mixture of cyclohexanone and cyclohexanol by liquid-phase air oxidation in the presence of a soluble cobalt catalyst. Subsequently, the cyclohexanol in the mixture is converted to cyclohexanone by vapor-phase dehydrogenation in the presence of a copper-magnesium catalyst.

Oximation and Beckmann rearrangement. Ammonia is oxidized by oxygen in the presence of steam, yielding nitric oxide, which is absorbed in a solution. This nitric oxide is hydrogenated over a palladium catalyst, in the presence of dilute sulfuric acid, producing hydroxyl ammonium sulfate solution. It reacts with cyclohexanone in stirred reactors in series to form the oxime. The heterogeneous outlet is neutralized with ammonia. Finally, the cyclohexanone oxime (Figure 3) is converted to caprolactam by Beckmann rearrangement, in the presence of oleum (concentrated sulfuric acid). The product of the rearrangement, caprolactam, is purified by neutralization, extraction in the presence of toluene, and distillation. The caprolactam melt is solidified and converted into flakes.

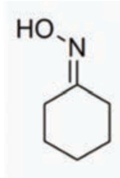


FIGURE 3. The structure of the oxime intermediate is shown here

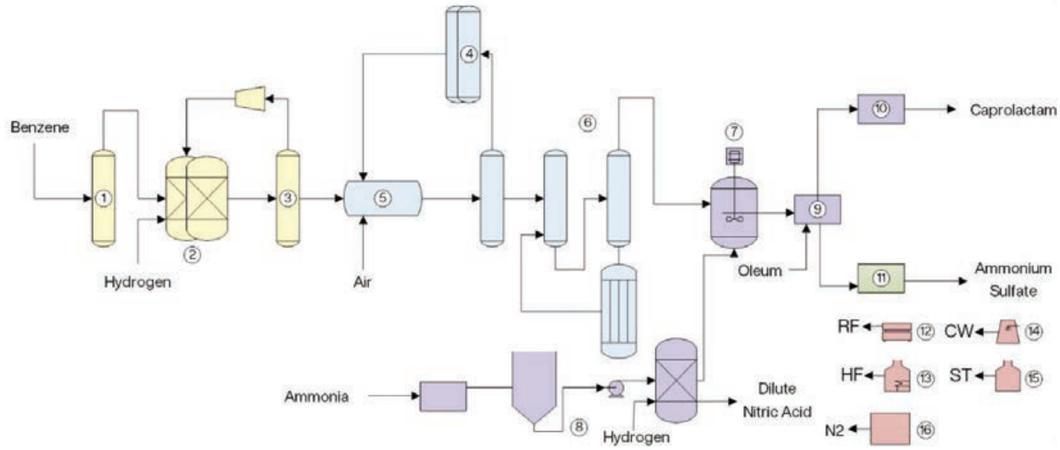
Ammonium sulfate purification. The ammonium sulfate solution that is removed in the neutralization steps is concentrated by evaporation. Then it is crystallized, centrifuged from the mother liquor and dried.

Production pathways

This organic compound can be produced commercially from cyclohexanone, cyclohexane, or toluene as starting materials. Most caprolactam production is based on the cyclohexanone process. To a lesser extent, caprolactam is produced commercially by the photonitrosation of cyclohexane or by nitrosation of cyclohexane carboxylic acid (derived from toluene) in the presence of sulfuric acid. Ultimately, the main commercial processes employed for caprolactam production are based on benzene or toluene from BTX (benzene, toluene, xylenes), and generate ammonium sulfate as a byproduct. ■

Edited by Scott Jenkins

Editor's note: Content for this column was originally developed by Intratec Solutions LLC (Houston; www.intratec.us) and is edited by *Chemical Engineering*. The analyses presented are based on publicly available and non-confidential information. The content represents the opinions of Intratec only. More information about the methodology for preparing the analyses can be found, along with terms of use, at www.intratec.us/che.



1. Benzene drying column
2. Hydrogenation reactors
3. Benzene purification
4. Cyclohexane recovery
5. Cyclohexane oxidation
6. Cyclohexanone purification
7. Oximation
8. $(NH_4OH)_2SO_4$ production
9. Beckmann arrangement
10. Caprolactam purification
11. NH_4SO_4 recovery
12. Refrigeration unit
13. Heat transfer fluid
14. Cooling tower
15. Boiler
16. Air separation unit

HF Heat transfer fluid
CW Cooling water
RF Refrigeration fluid
ST Steam
BFW Boiler feed water
N_2 Nitrogen

FIGURE 2. This process diagram depicts the production of caprolactam from benzene

Project Development: The Importance of Cost Estimating

Following a standardized project-development process, in combination with a robust cost-estimate classification system, can help to ensure that projects meet their financial goals

Larry Dysert
Conquest Consulting Group

IN BRIEF

CAPITAL PROJECT COST ESTIMATES

PROJECT DEVELOPMENT PROCESS

FEL 0: IDENTIFY OPPORTUNITY

FEL 1: BUSINESS CASE

FEL 2: SELECT

FEL 3: DEFINE

ESTIMATING AND SCOPE DEFINITION

CLASS 5 ESTIMATES

CLASS 4 ESTIMATES

CLASS 3 ESTIMATES

Cost estimating is critical to support decision-making during the project development process for projects in the chemical process industries (CPI). During the early phases of the project development lifecycle, cost estimating supports value-based decisions on project capacity, technology selection, location, execution strategies and many other factors. Eventually, cost estimating is a driver — if not the primary driver — to the final approval and funding authorizations that allow a proposed chemical project to proceed to construction and eventual startup.

Most CPI projects are approved based on the economic analysis of potential returns on the capital project investment cost. The basis for the investment cost is the capital project estimate. Until final sanction of the project (project authorization), it is important to realize that all the engineering and design efforts (expended over perhaps months, if not years) to support project authorization have been completed for a proposed project. Unless the project economic analysis, based on the cost estimate, meets targeted or acceptable rates of return, the project will not be approved and constructed. The technical deliverables defined during the early stages of the project development lifecycle must support effective estimating of the capital project cost to ensure that the resulting economic analysis is comprehensive, robust and sufficiently accurate to support the decision for final approval of the project (and the commitment to authorize the funds to complete the project through detailed design, construction and startup).

FIGURE 1. There are numerous project-development steps leading up to final approval and commencement of construction for capital projects in the CPI

Capital project cost estimates

In its most general terms, a cost estimate is a prediction of probable costs. For capital projects, a cost estimate is defined as "the prediction of the probable costs for a project or effort, for a given and documented scope, a defined location, and a point of time in the future [*1*]."

A capital project is the undertaking to develop, build or improve a capital asset (such as a chemical plant). These are typically long-term projects that involve various stages of project development, leading to eventual project approval and construction of the asset facilities (Figure 1). Thus, capital projects are temporary efforts with a defined beginning and end. They take resources and time to accomplish, and every individual project is a unique undertaking of interrelated tasks. Even when the physical and technical scope is essentially the same (such as for repeat projects of similar facilities), differences in location, time of construction and other issues, such as contracting strategy, may cause cost variability between the projects.

As a predictive process used to quantify, cost and price the resources required by the scope of a capital project, cost estimating is a challenging exercise. The estimator must evaluate the unique combination of materials

and labor resources required by the project scope, and calculate the associated costs to provide a cost estimate for a project that will be completed in the future.

The estimator attempts to base the cost estimate on as much fact (or certainty) as possible, but at the time of estimate preparation, all of the facts are never available. The estimator (and the estimate stakeholders) must accept that opinion and judgment will be required to prepare an estimate, because the scope of the project is not completely defined at the time of estimate preparation. In addition, all estimates are based on assumptions of future events and conditions.

Obviously, the goal is to reduce the level of uncertainty given the quality and maturity of project definition to support the estimate by using a disciplined estimating process, applicable estimating methodologies and appropriate material and labor cost references. However, in the end, as predictions, all cost estimates involve uncertainty, and the evaluation and communication of that uncertainty is another important step of the estimating process.

Project development process

Most large capital projects will follow some form of a stage-gate (or phase-gate) project development and governance process. The process defines the incremental development of the technical and other project deliverables over time that lead to project sanction and extends to project execution and the eventual startup of the facilities and turnover to facility operations [2].

The stage-gate process supports risk management for the project owner (or financer) by committing funds incrementally for each stage, with a review to support a decision to proceed (called the gate) at the end of each project development stage. If the project economics, schedule or other goal of the project (for instance, capacity or quality), evaluated at the end of a stage do not meet the objectives of the project stakeholders, then the project can be canceled before a commitment of full project funding has occurred. Alternatively, if project objectives are not being met, then project scope or other characteristics may be modified and the project may be recycled through an earlier stage of development.

Figure 2 illustrates a typical stage-gate project development process. The stages leading up to project sanction are often referred to as the front-end loading (FEL) process. This will typically involve incremental maturity of technical engineering and supporting project deliverables to eventually support a decision to fully authorize a project.

Much of the chemical industry has adopted a cost-estimate classification structure defined by AACE International (Association for the Advancement of Cost Engineering;

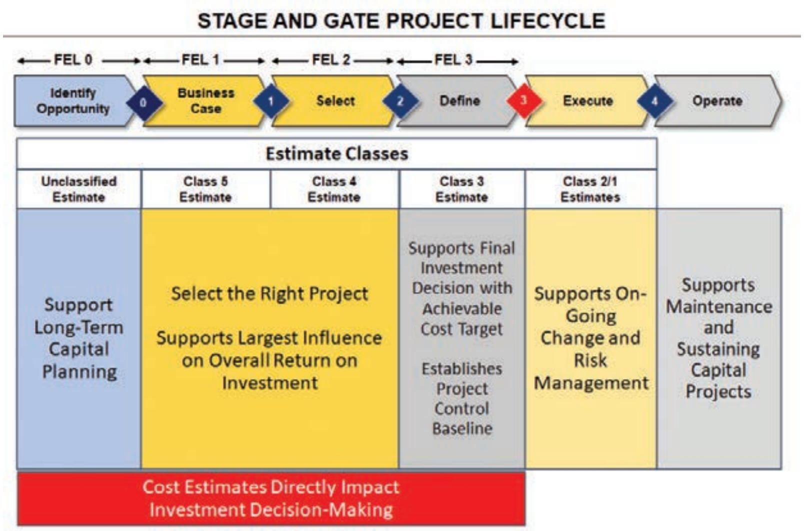


FIGURE 2. The stage-gate development process provides a standardized framework that engineers can follow to help shape their cost estimates throughout a project's lifecycle

FIGURE 3. During the FEL 2 phase, many documents will be prepared, including equipment lists, plot plans, instrumentation philosophy and equipment layout diagrams

Fairmont, W. Va.; web.aacei.org), a professional organization supporting the cost estimating and cost engineering community [2]. The defined estimate classes identify the maturity level of the engineering and technical deliverables that are expected to be generated during each stage of the project development process.

The following briefly describes the project development stages FEL 0 through FEL 3, which is typically the stage culminating in project authorization, and the corresponding cost estimates that are prepared to support the gate decision at the end of each stage.

FEL 0: Identify opportunity

This stage is typically performed by a business unit within an owner organization, usually without support of a project team. This stage involves the long-range identification of potential opportunities to create a new facility or asset, or modify an existing facility or asset. The business unit may prepare a cost study or unclassified estimate to support a Gate 0 decision to include the potential opportunity in the long-range capital planning budget of the owner organization (as identified in Figure 2).

Typically, little formal participation from engineering is involved in defining the overall scope of the proposed project during FEL 0, and the technical definition of the project does not meet the expectations of a formal classified estimate. Generally, the unclassified estimate for FEL 0 may be prepared using analogy estimating techniques, often without the involvement of a trained estimator.

FEL 1: Business case

If the owner organization decides to further investigate a potential project, it will authorize funds to create a small core project team to begin the FEL 1 stage. The goal of this stage is to progress the maturity of engineering and project deliverables to support preparation of a Class 5 estimate. During this stage, various alternative schemes and designs may be considered, and a Class 5 estimate may be prepared for each alternative.

The scope and characteristics of the project (or each potential alternative) are developed to provide overall project definition, looking at considerations like capacity, technology or location. Technical deliverables, such as block-flow diagrams and selection of the proposed primary technologies to produce the eventual end products, are defined, as well as potential locations for the facility.

A Class 5 estimate will be developed to support preparation of a business case and the Gate 1 decision on whether the project should proceed to the next stage (FEL 2) or not. The technical definition remains at a very high level at FEL 1, and the Class 5 estimates are generally prepared using conceptual estimating techniques, such as analogy, capacity factoring or parametric estimating.

Class 5 estimates will be associated with a high level of uncertainty (corresponding with a relatively wide range of expected accuracy). However, the Class 5 estimate is not used to sanction the project. The goal for the Class 5 estimate is that it is sufficiently accurate to support the FEL 1 gate decision on whether to incrementally authorize only the required additional funds to move to the next phase of project definition.

FEL 2: Select

During the FEL 2 (Select) phase, the project team is expanded, and engineering is progressed to provide a much clearer picture of the specific scope for the proposed project. The preliminary equipment list with key design parameters should be developed, along with approved process and utility flow diagrams and corresponding heat and material balances. Preliminary plot plans and general equipment layouts should be prepared (Figure 3). All associated utilities, offsite requirements, infrastructure and site conditions should be defined. Identification of preliminary design specifications to understand the metallurgies required by the facility is important. A general description of the overall instrument and control philosophy should be prepared.

In addition to the technical deliverables, preliminary integrated project plans to identify anticipated contracting, procurement, fabrication and contracting strategies should be developed, as well as a preliminary master schedule for the project.

The Class 4 cost estimate to be prepared during FEL 2 is based on the more specific and mature level of scope defined by the FEL 2 technical and project deliverables. Typically, a Class 4 estimate will use an equipment-factored (or equipment-modeling) approach, and some portions of the estimate may use more

TABLE 1. DEVELOPING ANALOGY-BASED ESTIMATES
1. Find and review known analogous (similar) projects.
2. Remove costs for scope items in the analogous project(s) that are not in the scope of the project to be estimated.
3. Normalize the costs on the analogous project for the location and timing of the project to be estimated.
4. Adjust the normalized costs for differences in scope between the analogous project(s) and the project to be estimated.
5. Incorporate costs into the estimate for scope items in the new project but did not exist in the analogous project(s).

deterministic estimating methods. Using equipment as the factoring basis for the Class 4 cost estimate (at least for the battery-limit process units of the facility) stresses the importance that the FEL 2 equipment list is comprehensive. Identification of required minor and auxiliary equipment (even if key design parameters have not yet been identified) will be important to the estimator, as well as the equipment spare philosophy (for both installed and non-installed spares).

The Class 4 cost estimate supports an updated business case, and along with the other, better-defined project deliverables (such as project plans and schedules), forms the basis of the Gate 2 decision on whether to provide the incremental funding to further expand the project team to complete FEL 3.

If a single design alternative was not selected during FEL 1, then a single alternative should be decided upon by the end of FEL 2. Moving to FEL 3 with more than one potential design alternative can be an expensive proposition for the project owner and should be avoided.

The FEL 1 and FEL 2 stages are especially important due to the decision to select a single project alternative to carry forward to FEL 3. By the end of FEL 2, the goal is to select the most preferred design alternative (considering capacity, technology, location and so on) in the interest of cost and schedule to best meet the project objectives established by the owner. The decision to move forward based on the Class 4 estimate and its impact on project economics often have the largest influence on the eventual return on investment.

Deciding on the preferred option may involve choosing between an alternative that provides a 9% rate of return on investment versus an alternative with a 12% rate of return on investment. After selection of the preferred alternative (in terms of capacity, technology, location and other characteristics), FEL 3 and subsequent project-execution decisions will be largely based on attempting to preserve the planned rate of return on investment. During FEL 3 and project execution, it unfortunately becomes easy to negatively impact the rate of return on investment, but almost impossible to substantially improve upon the planned rate of return on investment.

FIGURE 4. In an example of deterministic estimation, material and labor costs over the linear pipe measure are used to calculate overall piping costs

FEL 3: Define

The FEL 3 stage is often referred to as front-end engineering and design (FEED). The goal of this stage is to expand the project team to complete the required engineering and scope development that "freezes" the overall design. Completion of the final equipment list (identifying all design parameters), all process and utility piping and instrumentation diagrams (P&IDs), final plot plans and arrangement drawings provide the required technical scope definition to support preparation of a Class 3 estimate that is sufficiently accurate to allow the project owner to make a final decision to fully authorize project funds to complete the project through commissioning and startup. Ensuring the Class 3 estimate is sufficiently accurate will also depend on the non-technical project deliverable (integrated project plans, project schedule and so on) meeting maturity and quality expectations as defined in the AACE recommended practice [2].

Freezing the overall design is not meant to imply that all engineering and design activities are complete, but that the defining engineering deliverables, such as the equipment list, P&IDs, plot plan and so on, are finalized and approved to progress to detailed engineering. One of the goals of the stage-gate process is to ensure that the engineering and project deliverables are evaluated during the gate review to confirm that they meet the maturity and quality expected for the gate decision. If they do not, then the gate decision should be to not proceed until the issue is corrected. When such a review process is followed well, then changes to the defining deliverables will not occur in later stages.

For owner organizations, Gate 3 (at the completion of FEL 3) is most commonly used to sanction the project, providing full funding for detailed engineering through startup (the completion of the capital project). The Class 3 estimate will typically be based on a deterministic estimating methodology. The individual components of the project, including civil engineering, concrete, steel, buildings, equipment, piping, electrical, instrumentation and coatings, are quantified, either through bills of materials generated from engineering models or from manual take-offs of materials based on review of engineering drawings. Appropriate material and labor resources are applied. Labor productivity and other pricing adjustments for unique site, project and market conditions will be incorporated. Typically, the level of factoring is minimized in a Class 3 estimate, although costs for some items may still be factored when the level of effort to deterministically quantify and price them is not worthwhile, and some scope items will still not be completely defined, even at Class 3.

Due to its importance in establishing the final funding authorization for a project, validating that the project and technical deliverables are of sufficient maturity and quality to support the final project funding decision is critical. Ensuring that the deliverables meet their defined expectations to adequately quantify the project scope and prepare the Class 3 estimate is a key responsibility of the estimator. If there are exceptions to the expected maturity or quality of specific deliverables, they should be mentioned in the basis of estimate document (that should accompany every estimate of any class) and considered during risk analysis to establish the expected estimate accuracy range.

The Class 3 estimate will also be used to establish the cost baseline, against which both progress and performance will be measured, for the remainder of the project. The estimate will establish control budgets to support bid or tender evaluations, monitor procurements, evaluate detailed engineering and construction performance and to monitor changes to scope and execution strategies.

Estimating and scope definition

As identified above, the transition from stage to stage in the project development process results in greater maturity of the technical deliverables and improved scope definition of the project. Accordingly, the methods to prepare the cost estimates for each stage will progress from analogy or highly factored techniques to more deterministic techniques — a natural progression to utilize the greater level of technical detail that become available over time.

Factored (or stochastic) estimating techniques use cost estimating relationships where the independent variables are something other than a direct measure of the unit of measure for the item being estimated. For example, for a Class 4 equipment-factored estimate, instrumentation costs (the dependent variable) may be factored from equipment costs (the independent variable). These factored estimating methods may consist of simple or complex modeling based on either the inferred or statistical relationship between the costs of the dependent variable and the costs (or other measure) of the independent variable [*4*].

In deterministic estimating, the independent variables represent (more or less) a definitive measure of the item being estimated. For example, piping costs will be calculated from the material and labor pricing (Figure 4) applied to the linear measure of pipe (the quantity of the independent variable). Deterministic estimates for large projects may be comprised of tens of thousands of individual line items (even when quantities are aggregated for similar items by work breakdown and other coding structures).

TABLE 2. SELECTED ANALOGY-ESTIMATING TECHNIQUES

Technique	Description
Capacity factoring	Capacity is used as one of the primary characteristic differences between the proposed new project and the analogous project(s). In the CPI, there is typically a non-linear relationship between cost and capacity [*4*, *5*, *6*]
End-product units estimating	Similar to capacity factoring, this method typically relies on developing the estimate from the analogy based on the end-product capacity units of a project, such as the barrels per day of production [*4*, *7*]
Physical-dimensions estimating	The physical dimensions (such as length, area or volume) of the estimated item are used as the primary driver of costs. For example, the estimate for a control building in a chemical facility may be estimated based on the area of the building [*4*]
Parametric estimating	This is typically a more complex estimating technique that may involve multiple cost-estimating relationships and the identification of multiple independent variables that will be correlated to cost (the dependent variable). A parametric model could involve cost-estimating relationships that may be linear or non-linear [*4*, *8*]

Class 5 estimates

During FEL 1, scope definition is at a very high level, often comprised of overall facility capacity, technology selection, location and other key parameters or characteristics to describe the overall facility. The corresponding Class 5 estimates are often prepared using analogy-based estimating techniques, such as capacity factoring based upon historical data from similar projects. Parametric estimating models based on regression analysis for key cost

drivers may also be used to prepare Class 5 estimates.

Preparation of analogy estimates rely on the use of cost ratios and metrics derived from various analyses of historical data for similar projects. The estimate may be developed based on a comparison with a single project or may be dependent on evaluating comparisons with multiple similar facilities. Table 1 provides a framework for developing analogy-based estimates.

The identification of similar analogous projects and the comparison of project characteristics (capacity, technology, metallurgy and so on) to support effective adjustments to the costs of the analogous project is essential to obtain a sufficiently accurate estimate. The estimator should have the capability to appropriately adjust costs for the differences in project characteristics, but may need to rely on technical experts, such as process and discipline engineers, to assist in the identification and assessment of those differences.

Adjustments for capacity, metallurgy and other physical characteristics will often rely on objective and established estimating adjustment factors. However, some adjustments for variances, such as complexity of the facility or other performance factors affecting installation, may require significant subjectivity to address the resulting cost impacts to the new project estimate. There are various techniques involved with analogy estimating, which are summarized in Table 2.

The Class 5 estimate prepared at the end of the FEL 1 project-development stage represents the first evaluation of project cost that is based on both estimating and engineering input. The value of the Class 5 estimate will typically become a management target cost for the project development as it continues through the stage-gate project development process leading to final authorization. Estimating and engineering must work together to ensure that the full scope of the project is understood and reflected in the cost estimate. Often, the inside battery-limit (ISBL) process units are adequately addressed. However, the outside battery limit (OSBL) areas (for example, offsites, utilities and infrastructure) are less well-defined, which may lead to under-estimation of project cost.

Class 4 estimates

During FEL-2, project definition has generally progressed to generate technical deliverables that more specifically define the project scope, including preliminary equipment lists, process and utility flow diagrams, heat and material balances, preliminary plot plans and general arrangement drawings. As chemical process facilities tend to be equipment-centric, most Class 4 estimates for chemical facility projects tend to use equipment-factored estimating methodologies or prepared using

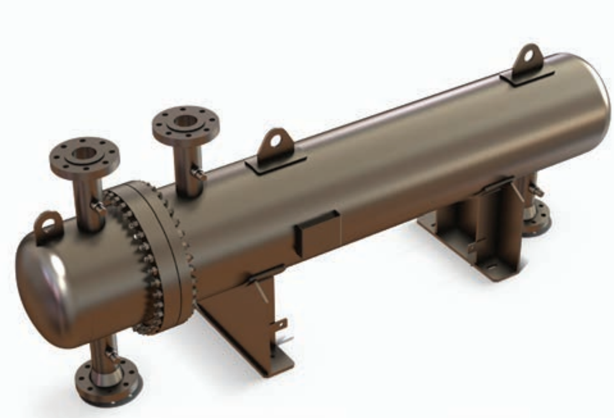


FIGURE 5. Equipment-factor estimating techniques will take into account equipment size and metallurgy, as well as the process conditions to which the equipment will be exposed. For example, the equipment-factor multiplier for a stainless-steel heat exchanger will differ from that for a carbon-steel unit

commercially available advanced engineering-estimating models.

Equipment-factored estimating techniques will typically depend on cost estimating relationships that relate the installed cost of a piece of equipment (including supply and installation of all associated bulk materials) to the purchase cost of the equipment item. For example, the installed cost of a pump may be estimated as 3.4 times the purchase cost of the pump. The cost multiplier is intended to account for the installed cost of the foundations, supports, piping, electrical connections, instruments and coating requirements that are associated with the equipment item — essentially all costs within a battery limit around the single equipment item [*5*, *9*].

The equipment-factor multipliers will vary by equipment type — there will be a different equipment-factor multiplier for a column versus a heat exchanger versus a pump. The equipment-factor multipliers will also vary based on the size, metallurgy and design conditions (pressure, temperature and so on) of the equipment item. As an example, the equipment-factor cost multiplier for a stainless-steel heat exchanger will be a smaller multiplier than for a carbon-steel heat exchanger, as the associated costs for foundation, supports and electrical connections do not increase proportionally with the increased purchase prices of the stainless-steel exchanger (Figure 5).

Other considerations that need to be considered by the estimator (typically as adjustments to the default equipment factors) are project-specific site and process conditions. If the plot area of the facility is constrained, requiring closer placement of equipment than is typical, that may necessitate adjustment to the equipment factors to account for the shorter runs of piping, conduit and wiring than for the average plant. Poor soil conditions or installation in an active seismic zone may involve adjustments to increase the piling and foundation costs for the equipment item. The equipment-factor multipliers may need to be adjusted for equipment installed in modules versus a stick-built approach.

For the equipment-factored approach described thus far, the installed costs of the equipment are factored from the purchase cost of the equipment (a cost-to-cost relationship). Depending on the granularity of the equipment factors, the factored costs may be in aggregate for the piece of equipment (a single total installed cost) or may generate costs by discipline that aggregate to the total installed cost for the associated equipment item.

Engineering-estimating models are usually commercial estimating applications that incorporate engineering modeling capabilities. Typically, the design parameters for a piece of equipment are entered into the application, and then the embedded engineering models will generate the quantities of the associated bulk materials (such as foundations or piping) based on default (but customizable) P&IDs and design specifications. The equipment itself may be priced from the estimating application (or directly input if a budgetary quotation price is available). Costs for installation are priced from the internal estimating databases based on the equipment and generated bulk materials.

With either equipment-factored estimating approach (equipment factor multipliers or engineering-estimating models), the costs for plant facilities not included within the estimating factors or not generated by the engineering-estimating model will need to be accounted for separately. For example, the costs of general site preparation, interconnecting pipeways, buildings, utility connections and underground firewater loops will often need to be estimated separately. The engineering-estimating model may be capable of generating these costs with additional design input; however, the costs for these items are not generally correlated directly with equipment items.

Engineering support is required by the estimator to ensure that the equipment list is complete and comprehensive, including all design parameters available. Although major equipment should be defined by the FEL 2 stage supporting the Class 4 estimate, auxiliary equipment may not yet be identified. Engineering will need to support estimating in the identification of auxiliary equipment costs that needs to be accounted for and included in the estimate. It will also be important to identify the level of design and sizing allowances that have been associated with the equipment items. It is common for equipment to be sized at 100% of operating duty during FEL 2, but in FEL 3 or detailed design, the sizing may be increased to account for some percentage of oversizing to meet project specifications.

Pricing of the equipment is also critical, especially with the equipment-factor multiplier approach. If the installed cost for a pump, for example, is factored using a 3.4 multiplier, then if the price of the pump is under-estimated by $1,000, the overall estimate is underestimated by $3,400. Both engineering and procurement should support estimating in the determination of the equipment pricing for the estimate.

The Class 4 estimate is typically used at the FEL 2 gate review to ensure that the cost of the selected design alternative (and the associated economic analyses) continue to meet financial targets to support the decision to continue to FEL 3. Gate 2 provides the project owner the op-

portunity to cancel the project if it is not justified or potentially to remain in FEL 2 to further develop project and technical deliverables before making a "go" or "no-go" decision. Engineering and estimating continue to work together to provide meaningful information to management to support the decision on whether to move the project forward. If project economics cannot achieve management targets, it is better to cancel the project early than to continue to invest in an economically sub-optimal project.

Class 3 estimates

Class 3 estimates are typically used in support of the full project-funding decision by project owners. Engineering and design will not be complete at the end of FEL 3 (supporting the Class 3 estimate). However, the maturity of the project and technical deliverables has progressed to allow a sufficiently accurate estimate to be prepared in support of project authorization. If the economic analysis supported by the Class 3 estimate meets the financial goals of the project owner and project authorization is approved, then the proposed project may proceed to become a finished project and transition to a producing asset of the organization.

The FEL 3 stage is used to complete the required technical definition to support detailed design (with the goal of no changes to the key defining deliverables). P&IDs, equipment lists, plot plans, arrangement drawings, electrical one-line drawings, instrument and control philosophy, specifications and so on should achieve "issued-for-design" status. In addition to the technical deliverables, other project deliverables, including the integrated project plan and project schedule should have progressed to meet the maturity expectations for the Gate 3 review.

The Class 3 estimate is usually a deterministic estimate based upon detailed quantification of as much of the project scope as possible. If the engineering and design information has been incorporated into an engineering model, then the model may be able to support a detailed quantification of the project scope (equipment and bulk materials). Any gaps in the model may be supplemented by a supplemental quantity takeoff from the available design drawings, whether by engineering or by estimating [*5*].

The detailed quantification is priced by the estimators for purchase, fabrication and installation costs as required. As design is not complete, there will still be the need for some costs to be accounted for by estimate allowances, and certain categories of costs will continue to be factored. Engineering supports estimating by ensuring that the Class 3 estimate accounts for all elements of project scope.

As the decision points to support full-funding authorization of a project, Gate 3 in the project development process is critical. It decides whether the months or years of project and design development will be realized by a constructed facility. Estimators should always be included in gate reviews to provide perspective on the estimate in relation to the gate decision, and especially for Gate 3 reviews.

The estimator must objectively describe the level of project definition that supported estimate preparation. Project organizations are often under pressure to complete activities and meet scheduled gate reviews. Thus, there will be expectations that a specific class of estimate be prepared at each stage of project development. The estimator should be unbiased in identifying the actual class of estimate achieved based on the project and technical deliverables that were provided to prepare the estimate. The estimator should identify any exceptions to deliverables that did not meet the intended level of maturity and quantify the resulting impact to uncertainty so that decision-makers have the best information on which to base their funding decision.

A standardized project development process, in combination with an estimate classification system, is key to providing the right maturity of design development to support the various estimates prepared during the project lifecycle. Engineering supports effective cost estimating by ensuring that the maturity of the design deliverables meet the expectations required by each project development stage and the estimating methodologies used for each stage. Effective estimating requires close coordination between estimators and engineers. In the early stages of project development, it ensures that the right alternative or project is selected to proceed to later stages of development. By Gate 3, it ensures that the project has the correct budget to be executed effectively and meet all project goals and objectives. All estimates support decision-making that eventually turn proposed projects into producing assets of an organization. ■

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References

1. AACE International, Recommended Practice 10S-90: Cost Engineering Terminology, March 2021.
2. Dysert, L. R., Supporting Estimates with Effective Scope of Work Definition, 2020 AACE International Transactions, Morgantown, W. Va., 2020.
3. AACE International, RP 18R-97: Cost Estimate Classification System - As Applied in Engineering, Procurement, and Construction for the Process Industries, August 2020.
4. Dysert, L. R., Early Conceptual Estimating Methodologies, 2020 AACE International Transactions, Morgantown, W. Va., 2020.
5. Dysert, L. R., Sharpen Your Estimating Skills, *Chem. Eng.*, June 2003.
6. Remer, D. and Chai, L., Estimate Costs of Scaled-Up Process Plants, *Chem. Eng.*, April 1990.
7. Dysert, L. R., So You Think You're An Estimator, 2005 AACE International Transactions, Morgantown, W. Va., 2005.
8. International Society of Parametric Analysts, "Parametric Estimating Handbook," Fourth Edition, Vienna, Va., 2008.
9. Hand, W.E., Estimating Costs from Process Flow Sheets, AACE Professional Practice Guide to Parametric and Conceptual Estimating, 3rd Edition, 2012.

Author

Larry Dysert is the managing partner of Conquest Consulting Group (CCG; Email: ldysert@ccg-estimating.com; Phone: 1-971-221-2101). He has been actively involved in many of CCG's consulting areas, including providing cold-eyes estimate reviews, estimate preparation, cost engineering organizational development, project controls, risk management, training and claims/dispute resolution support. Dysert has over 40 years of project estimating, management, consulting, and training experience in the chemical, petroleum, oil sands, high technology, utility generation, manufacturing and construction industries, and has been responsible for the preparation of conceptual and detailed estimates for capital projects, domestic and international, ranging to over $25 billion in size. He is a frequent presenter and author on estimating and cost engineering topics. Dysert holds several professional certifications related to cost estimating and decision and risk management. He is also an Award of Merit recipient, Honorary Lifetime Member and Fellow of AACE International and previously served as the vice president of the Technical Board for AACE International.

Explosion Protection: Considerations for Combustible Dusts

Managing the risk from combustible dust explosions involves a number of strategies for preventing explosions, as well as isolating, venting and suppressing explosions if they occur. Complying with applicable NFPA standards is a pathway toward minimizing risk

Clive Nixon
BS&B Pressure Safety Management

IN BRIEF

Combustible dust explosions present an ongoing risk to plants within the chemical process industries (CPI) that handle combustible powders or bulk solids. While dust explosions are not as common as fires, if an explosion occurs, the potential for extensive damage can be an order of magnitude higher. Managing dust explosion risks involves a number of strategies, including reducing the likelihood of an explosion through prevention activities, as well as implementing measures to isolate, vent and suppress explosions if they do occur.

Safety measures established by the U.S. Department of Labor's Occupational Safety and Health Administration (OSHA; Washington, D.C.; www.osha.gov), through the OSHA Combustible Dust National Emphasis Program, provide a good basis for combustible dust safety. The program recommends following practices in applicable National Fire Protection Association (NFPA; Quincy, Mass.; www.nfpa.org) standards. This article presents an overview of NFPA standards that are relevant for combustible dusts, along with considerations for managing combustible dust risks.

Dust explosion science

Dust explosion hazards exist in a wide range of industries, including chemical, petrochemical, grain, food, wood, paper and pharmaceutical industries. If the material being processed is combustible and capable of generating dust, then there is a potential dust explosion hazard. Common process equipment that presents an explosion risk include dust collectors, filter receivers, pneumatic conveyors, mechanical conveyors, size-reduction equipment, dryers, bins and storage silos.

A deflagration is an expanding flame front travelling through a fuel-air mixture at a velocity lower than the speed of sound. The resulting hot expanding gases rapidly pressurize any containing vessel, causing it to explode, unless it is capable of withstanding the full explosion pressure. This pressure can exceed 100 psi. The maximum explosion pressure is referred as P_{max}, and is commonly expressed in the units barg. P_{max} is one of several combustion characteristics referenced for protection system design. Others include the following:

- P_{max} (barg) — Maximum explosion pressure
- K_{st} (bar·m/s) — An explosibility index determined from measuring the rate of pressure rise with respect to time in a test vessel
- Minimum ignition energy (MIE; mJ) – The minimum ignition energy needed to ignite the fuel-air mixture
- Auto-ignition temperature (°C) — The lowest temperature at which a dust layer or dust cloud will spontaneously ignite. These are determined by two different test apparatuses
- Minimum explosible concentration (MEC; g/m^3) — The minimum concentration of a combustible dust in air that will support a deflagration

These explosibility characteristics are affected by the physical characteristics of the material. For example, grinding a material and reducing the particle size can increase the rate of combustion and increase the K_{st} value. It is therefore important that the specific material being handled is tested. If published data are used, care should be taken that the data correspond to a material that is representative of the material being handled.

Fire and explosion prevention

Deflagrations can occur both within process equipment and from the ignition of dust external to the process. To reduce the potential for deflagrations external to the process, electrical components, such as lights and motors, should be suitably rated accord-

ing to the area hazard classification, which is based on the frequency of dust being present and the characteristics of the dust. The method of determining area classifications is detailed in the National Electric Code, NFPA 70, Article 500 Hazardous (Classified) Locations. Additionally, it is important to note that effective dust control and housekeeping is key to limiting the potential for external deflagrations. From a cost standpoint, the best approach is to limit fugitive dust through adequate dust collection and by maintaining a sealed process. Regular cleaning of all horizontal surfaces, including roofing supports, is a costly alternative to keeping the dust contained in the first place. Blowing down the process with compressed air can create a deadly combustible dust cloud and must be avoided. Housekeeping and dust control are detailed in NFPA 652.

Within process equipment volumes, unless it is possible to fully contain the maximum explosion pressure, displace the oxygen or to operate below the explosible dust concentration, the primary method of reducing the potential of a deflagration is to monitor and prevent potential ignition sources. Potential ignition sources include:

- Overheated bearings
- Mechanical equipment failures, such as impact sparks from a hammer mill
- Rubbing or slipping conveyor belts
- Static electricity
- Foreign material entering the process
- Exothermic chemical reactions
- External welding or other hot work
- Process overheating

Having identified potential ignition sources, risk management solutions can be applied, such as bearing temperature monitoring. Testing the material being handled to determine its MIE and auto-ignition temperature will be helpful in determining the best prevention strategies.

Explosion protection

While methods such as monitoring and controlling potential ignition sources are key aspects of explosion prevention, they do not completely eliminate the risk. This necessitates the application of solutions to manage the pressure and flame in the event of a deflagration and prevent propagation to adjacent process volumes. NFPA 652 recognizes the following passive and active methods of protection:

- Reduction of oxidant concentration
- Deflagration venting
- Deflagration venting via flameless vents
- Deflagration pressure containment
- Deflagration suppression
- Dilution with a non-combustible dust to render the mixture non-combustible

Of the methods of protection listed, the most common are explosion venting and explosion suppression (Figure 1). We will discuss these approaches in more detail.

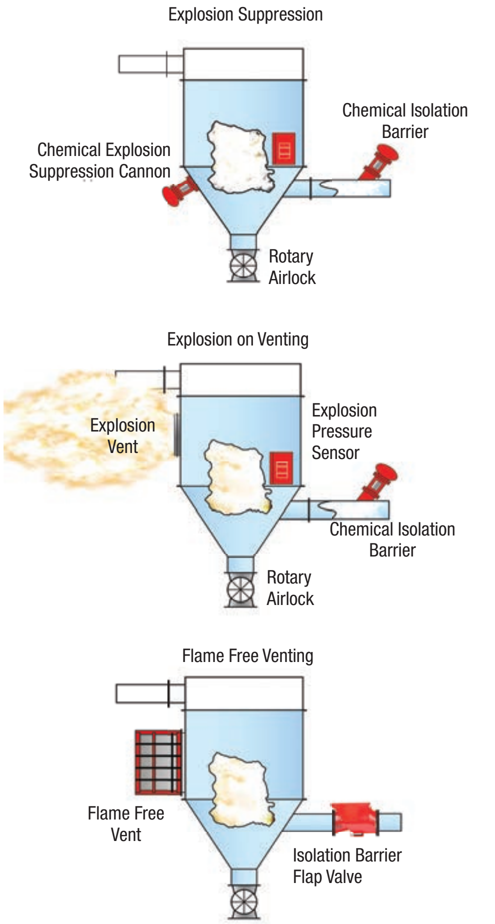

FIGURE 1. A number of approaches can be used to mitigate dust explosions, including isolation, venting and suppression

Dust explosion venting

During the early stages of a dust or gas explosion, explosion vents quickly open at a predetermined burst pressure, allowing the rapidly expanding combustion gases to escape into the atmosphere and limit the pressure generated inside the process equipment to calculated safe limits. Venting is the most widely adopted protection mechanism because it provides an economical solution and is often considered "fit-and-forget" solution. However, it is important to note that vents need to be regularly inspected, according to guidance contained in NFPA 68.

For decades, explosion vents have traditionally been designed using a "composite" approach that sandwiches plastic film between more resistant stainless-steel sheets with holes or slots cut into them. These vents are designed to open at typically 1 to 1.5 psi set pressure. With this type of technology, over time, the holes and slots in the stainless-steel sheets can admit particulate matter and debris. The buildup of solids can eventually affect the functionality of the vent. A vent that becomes heavier in weight will open slowly and less efficiently.

A better solution is a single-section explosion vent, comprised of a solitary sheet of stainless steel in a domed configuration. Perforations around the perimeter aid opening at the desired low-set pressure are protected with gasket materials. The single-section domed design produces a vent that is more robust, lighter in weight and largely eliminates the potential for buildup or contamination.

Despite their popularity, explosion vents will not work for every application. With venting, the combustion process releases a large ball of flame into the atmosphere. While this might be an acceptable consequence for outdoor equipment, such as silos, for applications within a plant, it could endanger personnel or equipment, and even lead to a secondary explosion.

BS&B Systems

FIGURE 2. Explosion suppression equipment detects an explosion in the first few milliseconds of the event, then releases a flame-quenching substance

In cases where a flame ball must be avoided, flameless venting can be deployed. Flameless vents incorporate an enclosure covering the non-process side of the explosion panel. This enclosure provides a path to atmosphere for the expanding hot gases through a stainless-steel mesh which absorbs the heat and prevents the transmission of flame. This style of vent adds considerable weight, due to the size and construction of the enclosure. External supports may therefore be required. When evaluating the cost of this solution, explosion isolation needs to be considered. This isolation is normally incorporated into the design of explosion-suppression systems. This should be considered when comparing flameless venting solutions to explosion suppression.

Suppression equipment

For processes where an explosion would ideally be prevented altogether, suppression systems are the optimal alternative. Explosion suppression equipment detects a dust explosion in the first milliseconds of the event, signaling explosion suppressors to rapidly release a flame-quenching medium, such as sodium bicarbonate, into the process equipment (Figure 2). This effectively stops the explosion in its infancy and results in a reduced explosion pressure that is safe for the protected equipment.

For a process running 24 hours a day, 7 days a week, a suppression system can be desirable because the speed of cleanup and refit allows for a quick return to production. In contrast, with venting or flameless venting, the explosion fully develops in the process equipment, requiring cleanup, attending to fire-related damages and other consequences that take time before the process can be brought back into operation. A typical suppression system consists of sensors and several explosion suppressors that propel an extinguishing agent into the process equipment. Pressurized nitrogen is typically used to provide the motive power.

Explosion isolation

In the event of a deflagration, there is a potential for the flame front to propagate via interconnections between equipment volumes, triggering secondary explosions of increasing severity. For this reason, where a dust explosion hazard exists, NFPA 652 calls for isolation devices in accordance with NFPA 69. Isolation methods accepted by NFPA 69 include the following:

- Chemical barriers
- Flap valves
- Float valves
- Pinch valves
- Slide-gate valves
- Material chokes (rotary valves)

Broadly, explosion isolation can be categorized as passive or active, per NFPA 69. A common example of passive isolation is a flap valve, which is most commonly installed horizontally as a one-way valve on the inlet duct to a dust collector. The flap is open during normal operation, latching closed against a seat in response to the cessation of air flow and a pressure wave traveling in the opposite direction. Recent advances in flap-valve design enable some models to be installed vertically and in ducts where the direction of airflow is in the same direction as the potential fireball. This enables them to be used, for example, on the exhaust duct of a dust collector.

An example of an active isolation method is chemical isolation, which typically consists of an explosion pressure detector that triggers a chemical suppressor. Chemical isolation is not limited to duct orientation or air flow direction. Furthermore, chemical isolation can be used on rectangular ducts and casings with moving internals such as drag conveyors. Chemical isolation does not restrict the pipe in any way, eliminating concerns about pressure losses.

NFPA dust standards

Plant owner/operators are required to document the risk of dust explosions at their faciltities in the form of a Dust Hazard Analysis (DHA), the scope of which is detailed in NFPA 652 (Standard on Fundamentals of Combustible Dusts). The deadline for implementing this DHA was September 7, 2020. The DHA is applicable to existing plants, processes and new projects. In NFPA 61, for the food and grain industry, the deadline has been extended to January 1, 2022 for existing plant and processes. The main components of a DHA are the following:

- Identifying where in the process or facility the potential exists for fires and explosions. This involves determining material combustion characteristics, identifying potential ignition sources, identifying external dust emissions, and noting the potential for explosion propagation between interconnected equipment volumes and building compartments
- Identifying safe operating ranges
- Identifying existing protection strategies and equipment
- Providing a plan for implementation of any additional protection equipment and strategies needed to manage the risk

A range of safety measures are available to process-plant owner/operators in meeting the OSHA Combustible Dust National Emphasis Program requirements. These are documented within the NFPA standards 61, 68, 69, 652, 654, 655 and 664. Compliance with these standards ensures that your process plant upholds a level of safety is acceptable to employees, the general public, the allied industry, state and federal fire marshals, insurance companies, and OSHA.

Understanding NFPA standards

In response to the 2008 fatal explosion of an Imperial sugar refinery, OSHA created the Combustible Dust National Emphasis directive, which outlines policies and procedures that create or handle combustible dusts. Violations to the OSHA NEP result in fines. States may provide and administer their own programs, which, if not identical to the federal requirements, must be at least as effective. No state is exempt from compliance with the intent of the OSHA NEP.

The directive states that "NFPA standards should be consulted to obtain evidence of hazard recognition and feasible abatement methods." Therefore, NFPA standards are the foundation of OSHA's enforcement tools for managing combustible dust hazards. OSHA hasn't created its own combustible dust standards, which is why the NFPA standards remain the basis for managing combustible dust hazards.

The relevant NFPA standards are described below.

NFPA 652. NFPA 652 provides a framework for the minimum requirements to be met for protecting against dust explosions and includes the requirement for a DHA. NFPA 654 provides prescriptive solutions for dust explosion protection without being specific to a particular commodity or industry. All industries with combustible dust hazards are required to comply with this standard. The reasoning leading to the development NFPA 652 standard came from users trying to follow the standards for combustible dust hazards but finding discrepancies and conflicting, inadequate explanations. NFPA 652 provides the minimum requirements that must be met for managing combustible dust hazards. This does not eliminate the need to meet the requirements of industry or commodity specific standards.

NFPA 654. NFPA 654 is the Standard for the Manufacturing, Processing and Handling of Combustible Particulate Solids. This standard provides safety measures to prevent and mitigate fires and dust explosions in facilities that handle combustible particulate solids. It includes prescriptive measures to protect a range of process equipment such as dust collectors, conveyors and dryers. It is not industry- or commodity-specific, and is therefore applicable to a range of industries and commodities not covered by other specific standards.

NFPA 68. NFPA 68 is the Standard on Explosion Protection by Deflagration Venting Standard on Explosion Protection by Deflagration Venting. This document focuses on explosion venting, that is, devices and systems that vent combustion gases and pressures resulting from a deflagration within an enclosure, for the purpose of minimizing structural and mechanical damage.

NFPA 69. NFPA 69 is the Standard on Explosion Prevention Systems, which covers the following methods for prevention of deflagration explosions: control of oxidant concentration, control of combustible con-

centration, explosion suppression, deflagration pressure containment, and spark extinguishing systems.

NFPA 61. NFPA 61 is the Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities. This standard covers all facilities engaged in handking dry agricultural bulk materials, including grains, oilseeds, agricultural seeds, legumes, sugar, flour, spices, feeds, and other related materials, such as starch.

NFPA 484. NFPA 484 is the Standard for Combustible Metals. This standard covers all metals and alloys in a form that is capable of combustion or explosion, and it outlines procedures that shall be used to determine whether a metal is combustible or noncombustible form. It also applies to processing or finishing operations that produce combustible metal powder or dust such as machining, sawing, grinding, buffing and polishing.

NFPA 664. NFPA 664 is the Standard for the Prevention of Fire and Explosions in Wood Processing and Woodworking Facilities. This standard establishes the minimum fire and explosion prevention requirements for facilities that process wood or manufactured wood products using wood or cellulosic fibers, creating wood chips, particles or dust. Examples include wood flour plants, industrial woodworking plants, furniture plants, plywood plants, composite board plants, lumber mills, and production-type woodworking shops and carpentry shops that meet minimum requirements for plant size or dust collection flow rates.

NFPA 655. NFPA 655 is the Standard for Prevention of Sulfur Fires and Explosions. This standard covers explosion and fire hazards encountered in the handling, crushing, grinding, and pulverizing of bulk and liquid sulfur.

Concluding remarks

There is always more than one way to achieve combustible dust safety. The expertise is in reviewing each option for a particular industrial process and arriving at a combination of housekeeping and technologies that is technically effective, as well as cost effective, in meeting the owner-operator's responsibilities under OSHA and NFPA standards. ■

Edited by Scott Jenkins

Author

Clive Nixon is a sales manager for BS&B Pressure Safety Management (7455 East 46th Street, Tulsa, OK 74145; Phone: 918-622-5950; Email: clive.nixon@bsbsystems.com). Nixon supplies explosion protection solutions to the food, chemical, wood, and grain industries, and has over 20 years of experience in the field of industrial explosion protection. He holds a degree in technical communications from Northeastern University, and an higer national certificate (HNC) in electrical and electronic engineering from Slough College of Technology in Berkshire, England. He has presented seminars on the subject of industrial explosion protection for the International Powder & Bulk Solids Conference/Exhibition Conference, Rosemont, Ill.; Interphex Pharmaceutical Manufacturing Conference & Exhibition, New York City; NFPA World Safety Conference & Expo, Baltimore, Md.; The Department of Engineering Professional Development, University of Wisconsin-Madison; Powtech, Sao Paulo; and e-Week, Albany, N.Y.

Can You Trust the Joukowsky Equation for Waterhammer?

The Joukowsky equation is often relied upon to determine the maximum possible fluid pressure inside a pipe, but there are certain scenarios where this equation does not return the expected conservative result for overpressurization

Trey Walters
Applied Flow Technology

IN BRIEF

We engineers love our formulas. Especially when we know they can quickly give us a conservative, worst-case answer.

As a young engineer in the aerospace and power industries, I participated in multiple meetings and read several reports that used the Joukowsky equation to determine a maximum possible fluid pressure inside a pipe. Since everyone "knew" that the Joukowsky equation predicted the maximum possible pressure, this was a quick and reasonable thing to do. Unbeknownst to my managers, colleagues and myself at the time, this was a potentially dangerous thing to do. Because while the Joukowsky equation often returns a conservative result, it cannot be relied upon to do so in every situation.

This article summarizes the important points of a recent journal article [*1*] that discusses three different situations for which the Joukowsky equation does not give a worst-case, conservative answer.

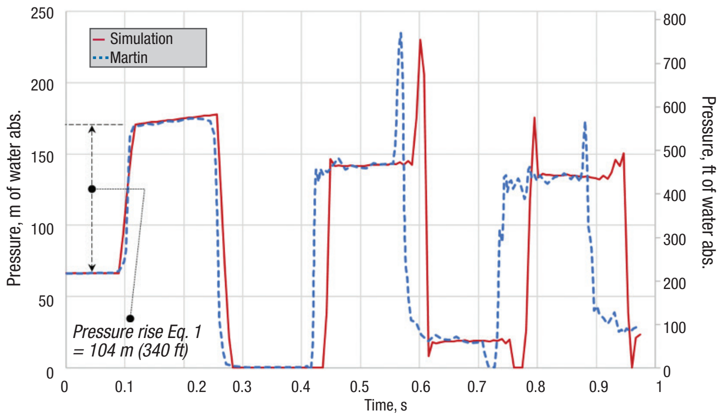

FIGURE 1. The graph shown here, from Example 2, illustrates the experimental and numerical predictions of pressures during transient cavitation, compared to the maximum predicted pressure from the Joukowsky equation (from Ref. 1)

The Joukowsky equation

The Joukowsky equation [*2*] relates the instant change in piezometric (hydraulic) head, *H*, to an instant change in velocity, *V*, often conceptualized as an instantaneous valve closure. The Joukowsky equation is sometimes referred to by other names, such as the "Basic Waterhammer Equation," the "Instantaneous Waterhammer Equation" or the "Maximum Theoretical Waterhammer Equation." The relationship is shown in Equation (1):

$$\Delta H_J = -a\Delta V/g \qquad \textbf{(1)}$$

where a is the wavespeed (also known as the celerity) and g is the acceleration due to body forces (32.2 ft/s^2 or 9.8 m/s^2 for stationary systems at the earth's surface) due to gravity. The wavespeed is related to the speed of sound in the liquid, but also includes pipe structural interaction. Note that the negative sign in Equation (1) means that a reduction in velocity leads to an increase in piezometric head. Equation (1) is more typically found in civil engineering applications, which frequently use piezometric head and hydraulic gradeline concepts.

The relationship between the change in piezometric head and pressure, *P*, is given by Equation (2):

$$\Delta P = \rho g \Delta H \qquad \textbf{(2)}$$

where ρ is the liquid density.

Combining Equations (1) and (2) results

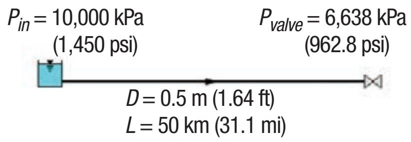

FIGURE 2. The diagram shows the system description for the horizontal pipe in Example 3

in a form of the Joukowsky equation that is more frequently used by chemical and mechanical engineers (Equation (3)).

$$\Delta P_J = -\rho a \Delta V \qquad \textbf{(3)}$$

Equations (1) and (3) are essentially equivalent ways of presenting the Joukowsky Equation, and will be used interchangeably in this article. Note that one limitation of Equation (1) is that when the system experiences zero gravity, Equation (1) would have a divide-by-zero problem. In such cases, Equation (3) retains validity and is thus preferred. During my time working in the aerospace industry, I frequently worked on zero-*g* systems, as well as those with much higher and lower body forces than 1 *g* (1 standard earth gravitational acceleration). See Ref. 1 for more on this.

The Joukowsky equation traces its history back to the 19th century. In fact, Joukowsky is the lucky author whose name is most often associated with Equations (1) and (3). However, a thorough review of the early literature shows that others derived this equation prior to Joukowsky — for applications in blood flow [3].

Limiting assumptions

Before discussing the cases where the Joukowsky equation does not result in a conservative answer, it should be realized that the equation has numerous limiting assumptions. From Ref. 1:

"*In principle, Equation 1 only claims validity the moment after the velocity decrease (e.g., valve closure). However, practicing engineers often apply it as if it retains validity both immediately after the velocity decrease/valve closure, as well as at all times thereafter, assuming that no other independent transients occur. Since Equation 1 is often applied in this manner, the limitations of this equation are discussed with respect to its validity after the initial transient occurs. These limitations are as follows*:"

- *Straight, constant-diameter piping of uniform material, wall thickness and structural restraints*
- *Uniform pipe friction*
- *Minimal friction pressure drop in piping (explained in a later section)*
- *Minimal fluid-structure interaction with the piping and supports*
- *No cavitation or gas release*
- *No trapped, or entrained, gases in the piping (that is, it is initially 100% full of liquid)*
- *No external heat transfer that can change any of the piping and fluid physical properties or cause phase changes*
- *Constant liquid density and constant bulk modulus*
- *One-dimensional fluid flow*
- *Linearly elastic piping material*

Example 1: Instant valve closure. Let's take a look at a simple example from Ref. 1. Consider a pipe of diameter (D) 0.5 m (1.64 ft) conveying oil with a specific gravity of 0.9 (the density, ρ, is 900 kg/m^3, or 56.2 lbm/ft^3). The volumetric flowrate, Q, is 0.4 m^3/s (14.1 ft^3/s) and the wavespeed, a (the propagation speed of the fluid transient), is 1,291 m/s (4,236 ft/s).

The pipe cross-sectional area, A, is given by Equation (4):

$$A = \pi D^2/4 = 0.196 \text{ m}^2 \text{ (or 2.11 ft}^2) \qquad \textbf{(4)}$$

Hence, the velocity change if a valve is closed instantly can be calculated with Equation (5).

$$\Delta V = \Delta Q/A = -2.04 \text{ m/s (or } -6.68 \text{ ft/s)} \qquad \textbf{(5)}$$

Therefore, from Equation (1):

$$\Delta H_J = -a\Delta V/g = -(1{,}291 \text{ m/s})(-2.04 \text{ m/s}) / (9.81 \text{ m/s}^2) = 268 \text{ m (or 880 ft)} \qquad \textbf{(6)}$$

And using Equation (3):

$$\Delta P_J = -\rho a \Delta V = -(900 \text{ kg/m}^3)(1{,}291 \text{ m/s})(-2.04 \text{ m/s}) = 2{,}367 \text{ kPa (or 343 psi)} \qquad \textbf{(7)}$$

Note that the value given by Equation (7) is the pressure increase due to waterhammer after an instant valve closure. To find the maximum pressure, the Equation (7) pressure increase must be added to the fluid's pre-existing, steady-state pressure.

Cases where the equation does not give a conservative result

Three situations where Equation (3) may not be conservative are: transient cavitation and liquid column separation; line pack; and piping system reflections (networks, components, area changes and surge-suppression devices).

These three cases will be explored in three examples discussed below.

As chemical engineers are keenly

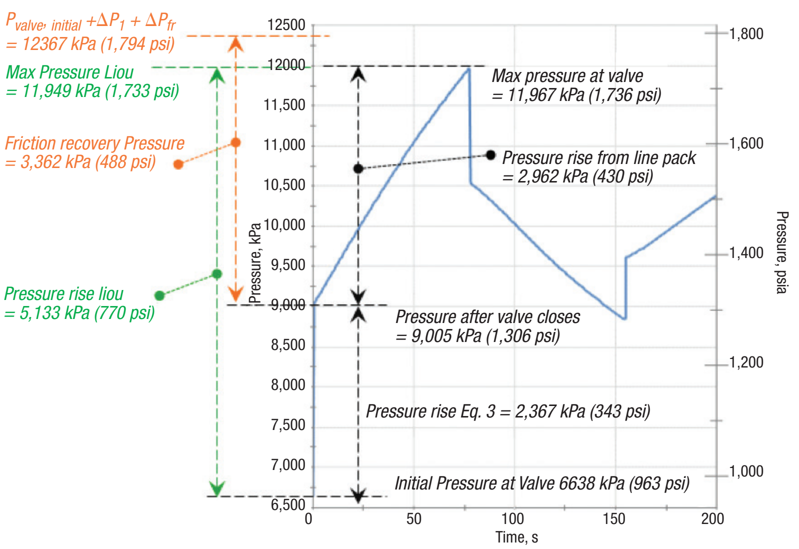

FIGURE 3. To illustrate Example 3, the graph shows the predicted pressure transient at the valve from the system from Figure 2, with pressure rise estimation methods (from Ref. 1)

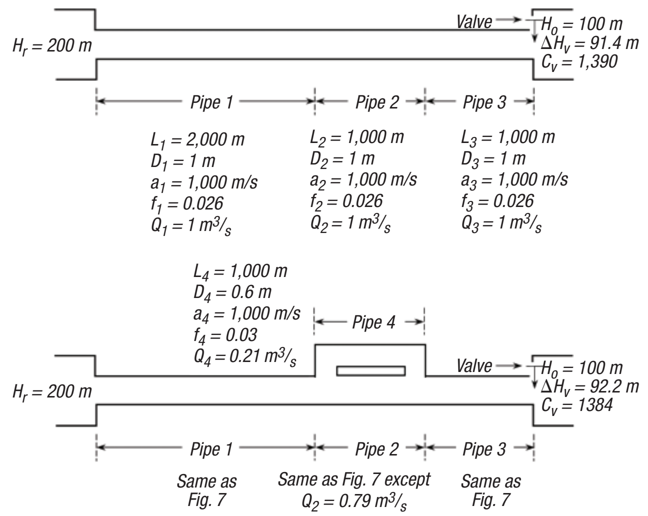

FIGURE 4. The diagrams accompany Example 4, depicting straight (top diagram) and networked (bottom diagram) piping systems (from Ref. 1)

aware, when liquid pressure drops to the local vapor pressure, the liquid will flash and vapor will be generated. This is called transient cavitation. It is transient because in a waterhammer situation, a reflecting transient pressure wave will typically and quickly repressurize the pipe and collapse the vapor. It is usually not a sustained, two-phase flow situation, but a temporary two-phase situation that quickly returns to single-phase in most cases.

If enough vapor is generated and flow conditions are right, the entire cross section of fluid can vaporize and the continuous column of liquid will have a vapor gap. This is true liquid column separation. In common use, transient cavitation and liquid column separation are synonymous terms.

It turns out that predicting the waterhammer pressure transients during and after transient cavitation has occurred is very difficult. The best available models are not very accurate, because the phenomenon is quite complex. As a result, waterhammer engineers treat predictions from simulation software in cases where transient cavitation occurs with great caution [*4*].

Moreover, it has been shown experimentally that when transient vapor pockets collapse, the resulting pressure spike can exceed the values returned by using Equation (3). Example 2 discusses this.

Example 2: Transient cavitation and vapor collapse. Figure 1 shows the experimental results [*5*] and the commercial software simulation results [*6*] for a 102-m (335 ft) coiled copper tube experiencing waterhammer. Equation (1) predicts a maximum pressure rise of 104 m (340 ft), resulting in a peak pressure (when added to the steady-state pressure) of 171 m (560 ft) near 0.1 s. Thus, the initial pressure rise agrees with Equation (1). However, the reflecting wave leads to a pressure decrease, and transient cavitation begins at this location at about 0.3 s. It lasts until just after 0.4 s. This is the point at which the system repressurizes and collapses the vapor cavity. Both the experiment and the simulation show a peak pressure that exceeds the result from Equation (1) at about 0.6 s. This peak is about 235 m (770 ft). Ref. 1 offers guidance on how to quickly check for the possibility of transient cavitation in your system.

Example 3: Line pack: recovery of frictional pressure drop. The term "line pack" is commonly used, but is not very descriptive of the process. So before trying to describe what the term is, consider a simple conceptual example. First, just think about a steady-state situation. Figure 2 shows a 50-km horizontal pipeline with conditions taken from Example 1. Additional details for the steady-state input data for Example 3 are shown here:

L = 50 km (31.1 mi)
D = 0.5 m (1.64 ft)
f = 0.018
Q = 0.4 m^3/s (14.1 ft^3/s), 1,440 m^3/h (6,340 gal/min)
V = 2.04 m/s (6.68 ft/s)
P_{in} 10,000 kPa (1,450 psi), fixed
P_{valve} 6,638 kPa (962.8 psi), upstream initial pressure
ΔP_{pipe} 3,362 kPa (487.6 psi), initial pipe pressure drop
ρ 900 kg/m^3 (56.2 lbm/ft^3)

The steady-state pressure drop is a simple calculation once the friction factor is determined (the Darcy-Weisbach f = 0.018). The pressure drop is thus 3,362 kPa (488 psid).

The question we ask here is: What is the pressure at the valve after it has closed, the flow has stopped, and all transients have died out? The answer is trivial. Since the entire pipe is horizontal, the pipe will have a pressure everywhere along its length that is the same as the inlet pressure of 10,000 kPa (1,450 psia).

Notice what happened here. The pressure at the valve increased. By how much? It increased by 3,362 kPa (488 psi). In fact, it increased by the same amount as the frictional pressure drop while it was flowing. This pressure increase has nothing to do with waterhammer. It is merely the increase in pressure when frictional pressure loss is no longer occurring. We will call this pressure increase the friction recovery pressure, ΔP_{fr}. In the present example, ΔP_{fr} = 3,362 kPa (or 488 psi).

During a pipeline transient, the frictional behavior interacts with the acoustic nature of the waterhammer wave such that a passing wave does not bring the fluid to a complete rest, even after a valve is closed. Ref. 7 contains an excellent summary of line pack:

"In pipeline transients, frictional resistance to flow generates line packing, which is a sustained pressure increase in the pipeline behind the waterhammer wave front after the closure of a discharge valve. This phenomenon is of interest to cross-country oil pipelines and long water transmission mains because the sustained pressure increase can be very significant relative to the initial sudden pressure increase by waterhammer and can result in unacceptable overpressures."

Ref. 7 offers a powerful new method to estimate the combined pressure rise due to line pack and waterhammer. The results will be discussed in the next section.

Now let's see what happens to the Figure 3 pipeline from a waterhammer point of view when the valve is closed. To determine this, we need additional information as shown here

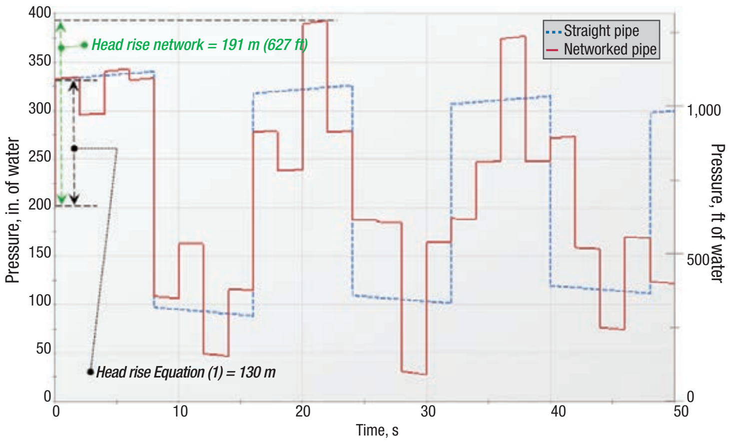

FIGURE 5. Simulation results at the valve from Example 4, using the straight and networked pipe systems in Figure 4 (from Ref. 1)

for Example 3, assuming instantaneous valve closure:

a = 1,291 m/s (4,236 ft/s), the wavespeed of the fluid

ΔV = –2.04 m/s (–6.68 ft/s)

Using Equation (3), the Joukowsky pressure rise (ΔP_J) can be determined to be 2,367 kPa (343 psi). This was shown in Equation 7. If an engineer took Equation 3 as the worst-case pressure rise, that person would add this to the initial valve pressure of 6,638 kPa (963 psia) to obtain maximum pressure of 9,005 kPa (1,306 psia). It is true that this would be the pressure rise immediately after the valve closed. However, this is not the maximum pressure, because the pressure will continue to rise after valve closure as the frictional recovery of pressure occurs.

A truly conservative maximum pressure rise can be obtained by adding the two together, as shown in Equation (8):

$$\Delta P_{max} = \Delta P_J + \Delta P_{fr} = 5{,}729 \text{ kPa (or 831 psi)} \quad (8)$$

The maximum possible pressure is then obtained by adding the Equation (8) pressure rise to the initial valve pressure (P_{valve}). This result is 12,367 kPa (1,794 psia), as shown in Figure 3, where the results from a full transient simulation are also shown. The method in Ref. 7 by Liou is shown also. Here, it is clear that the maximum pressure of 11,967 kPa (1,736 psia) is much higher than what is predicted by Equation (3).

The line pack pressure rise can be seen in Figure 3 from 0 to about 75 s, and totals 2,962 kPa (430 psi). With a keen eye for line pack now at our disposal, look back to the experimental results in Figure 1. After the initial Joukowsky pressure rise of 104 m (340 ft), it is evident that the pressure continues to increase for another 0.1 s or so. This increase is about 5 m (16 ft), which happens to be roughly the frictional pressure loss. Hence, one can see line pack in the Figure 1 experimental results, as well as the simulation results, when one looks closely.

Example 4: Reflected pressure waves. Ref. 1 discusses numerous ways that a reflected wave can cause a pressure rise greater than what would be given by Equation (3). Consider the systems in Figure 4, which shows a straight pipe system and a similar networked system. This example appears in Ref. 1 and was first published in Ref. 8.

In each system in Figure 4, the valve at the end is closed instantly. Figure 5 shows the results. It is clear that the pressure rise in the networked piping is higher than what would be predicted by Equation (1) at 20 s.

Numerous other situations can cause reflected waves that exceed the values obtained using Equation (3). These situations include a pipe diameter change, a branch going to a dead-ended pipe and the presence of a gas accumulator [*1*].

Concluding remarks

Waterhammer can be a complicated issue to address. When possible, a more detailed analysis than the simple Equation (3) should be considered. Ref. 9 provides some guidance to chemical engineers on how to approach this.

The Joukowsky equation is a powerful tool for engineers when used with a proper understanding of its limitations. Engineers should not assume that it always provides a worst-case, conservative pressure rise. The examples presented here clearly show cases where the pressure rise can be much larger than what the Joukowsky equation predicts. Keep this in mind the next time someone tells you they have calculated "the maximum theoretical waterhammer pressure." Just smile and reply, "are you sure you can trust that?" ■

Edited by Scott Jenkins

References

1. Walters, T. W. and Leishear, R. A., 2019, "When the Joukowsky Equation Does Not Predict Maximum Water Hammer Pressures," *ASME Journal of Pressure Vessel Technology*, Vol. 141 / 060801-1, December 2019.
2. Joukowsky, N., Über den hydraulischen Stoss in Wasserleitungsröhren. (On the hydraulic hammer in water supply pipes), Me´moires de l'Acade´mie Impe´riale des Sciences de St.-Petersbourg, Series 8, Vol. 9, No. 5 (in German, English translation, partly, by Simin, 1904). 1900.
3. Tijsseling, A. S., and Anderson, A., Johannes von Kries and the History of Water Hammer, *ASCE Journal of Hydraulic Engineering*, Vol. 133, Issue 1, pp. 1–8, 2007.
4. Bergant, A., Simpson, A. R. and Tijsseling, A. S., Water hammer with Column Separation: A Historical Review, *Journal of Fluids and Structures*, 22, pp. 135–171, 2006.
5. Martin, C. S., "Experimental Investigation of Column Separation With Rapid Closure of Downstream Valve", 4th International Conference of Pressure Surges, BHRA, pp. 77–88, Bath, UK, 1983.
6. Applied Flow Technology, AFT Impulse 8, Colorado Springs, Colo., USA., 2020.
7. Liou, C. P., Understanding Line Packing in Frictional Water Hammer," *ASME J Fluid Eng*, Vol. 138(8), New York, 2016.
8. Karney, B. W., McInnis, D., Transient Analysis of Water Distribution Systems, *Journal AWWA*, Vol. 82 (7), pp. 62–70, 1990.
9. Prentice, W., 2021, Understand and Mitigate Waterhammer in Fluid Processes, *Chem. Eng.*, March 2021, pp. 28–32.

Author

Trey Walters is the founder and president of Applied Flow Technology (AFT; 2955 Professional Place, Suite 301, Colorado Springs, CO 80904; Email: treywalters@aft.com; Phone: 1-719-686-1000). Walters founded AFT in 1993. He holds a B.S.M.E. (1985) and M.S.M.E. (1986), both from the University of California, Santa Barbara and is a registered professional engineer. Walters is the original developer of AFT Fathom, AFT Arrow and AFT Impulse and has taught hundreds of training classes on AFT's software products in twelve countries across every populated continent. He worked previously for General Dynamics in cryogenic rocket design and Babcock & Wilcox in steam/water equipment design. Walters is a fellow of the American Society of Mechanical Engineers.

Landfill Gas Processing: Plant-Design Considerations

There are several technologies used in the disposal of landfill gas (LFG). Here are some key elements that can guide engineers in designing an optimized LFG processing plant

Babak Firoozi
A/C Control, Inc.

People generate trash. Trash is stored in landfills. Landfills contain bacteria, which decompose the trash to produce combustible landfill gas (LFG) [*1*]. LFG is a hazardous, flammable greenhouse gas containing mainly methane (CH_4), along with many other components, including siloxanes, CO_2 and mercaptans, as well as asphyxiants like hydrogen sulfide (H_2S) and volatile organic compounds (VOCs). It also can be a valuable source of renewable energy.

If not disposed of properly, LFG can become an explosive and hazardous threat to nearby communities [*2*]. The minimum required disposal for LFG is incineration. This is typically used by smaller landfills, which do not generate enough LFG to produce a valuable volume of product. Direct-use methods, which are typically employed by medium- to large-size landfills, combust the LFG to take advantage of its heat content [*3*]. Electricity generation, cogeneration (cogen) of steam and electricity, boilers, kilns, iron forges and other thermal applications are typical direct-use applications.

Another method is conversion of LFG to pipeline-grade natural gas, which is sometimes used at large landfills. Pipeline-grade conversion is the most complicated of these methods, but could yield the greatest profit, depending on the price of natural gas. This article covers general design criteria and disposal methods used in the LFG industry. Various equipment and processing technologies, such as temperature-swing adsorption (TSA), pressure-swing adsorption (PSA), sulfur removal and thermal oxidization (TOX) are also discussed.

Consider economics

Economic analysis is the first step to select the best option from the available LFG disposal technologies (Figure 1). Plant economics are based on total LFG production during the peak production years of the landfill's life (when the produced gas is around 55 vol.% CH_4), usually from its fourth year to its fortieth year. Economic analysis must consider initial capital investment (capex) versus continued operational expenditures (opex). The size of the landfill is one factor to consider. Nearness to gas users is another factor. There may be little economic incentive to invest in a large, high-producing landfill if it is far away from energy-use infrastructure.

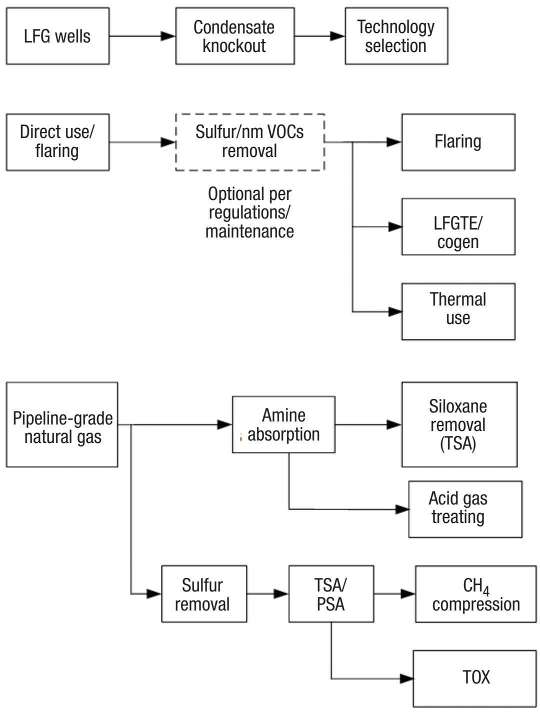

FIGURE 1. Landfill gas (LFG) can be handled using a number of technologies, depending on landfill size and economics

Flaring is usually considered by landfill operators who do not wish to risk capital investment. The economic break-even point is usually around 200 std. ft^3/min of LFG during peak production. Landfills with high sulfur production may require additional investment to meet environmental regulations.

Many combustion-based direct-use technologies require a moderate capital investment. LFG used in kilns, boilers, LFG leachate evaporators and other burning technologies may not require any additional treatment if the operator is willing to spend more money on continued maintenance. LFG-to-electricity (LFGTE) production represents over 50% of the world's direct use of LFG [*3*]. LFGTE projects typically generate 0.8 to 3 MW of energy, corresponding to approximately 200 to 750 std. ft^3/min of LFG.

The profitability for purification of LFG to pipeline-grade natural gas is directly related to local spot prices.

LFG collection

LFG collection and condensate disposal design is the same for all LFG processes (Figure 2). LFG is drawn under low vacuum through underground wells and passes through a common header to a moisture separator. A blower transfers the LFG to the process, and a pump transfers the condensate to storage or back to the landfill.

LFG header and blower. LFG is collected through gas wells into a common header. The LFG is drawn to the

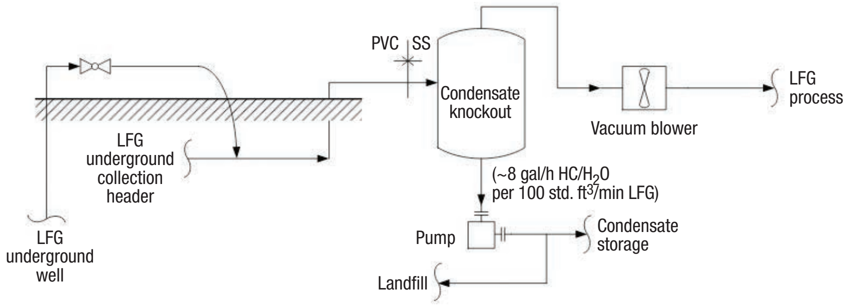

FIGURE 2. Condensate collection and disposal is an important consideration in LFG processing

LFG header based on the differential pressure between atmospheric pressure and the vacuum blower. On high-pressure days, more LFG is collected. Typically, the process engineer will design the LFG collection system to provide about 40 to 60 in. H_2O vacuum at the suction of the blower [4]. The vacuum blower should be robust enough to handle gas with solid particles. A sliding-vane or liquid-ring blower is usually selected. Liquid-ring type blowers are much more expensive than sliding-vane, but they also provide improved reliability. Blower selection should consider capex versus opex.

LFG condensate knockout. LFG is collected at 100% relative humidity at about 140°F [4]. The warm LFG cools to about 90°F in the collection header, where some of the vapors condense. The condensate is separated in the LFG knockout vessel. LFG condensate is considered a hazardous waste because it contains halogenated organic compounds, sulfur compounds, aromatics and other aggressive chemicals that lower the pH to a range of about 4.2 to 5.0. The condensate collection header is usually designed with polyvinyl chloride (PVC), and the pipes and vessel metallurgy are usually stainless steel [5].

LFG condensate must not be drained to the sewer because it is a hazardous waste. It is either pumped back to the landfill or transferred to a hazardous-wastewater treatment facility. Condensate that is pumped back to the landfill is absorbed by the solid waste at the beginning of LFG production. Toward the end of its life, the landfill is saturated and the condensate must be treated as hazardous waste. At that time, the condensate is pumped to a polyethylene tank for storage and periodically transferred to a hazardous wastewater-treatment facility. Condensate contains both water and non-methane volatile organic compounds (nmVOCs). The nmVOCs could be as high as 0.6 mol% [1], or roughly 1 gal/h of hydrocarbon condensate per 100 std. ft^3/min of LFG.

Water condensate is calculated as 100% relative humidity LFG cooled from 140°F to 90°F. The mass humidity ratio (x) is the ratio of the mass of water (m_W) to the mass of dry LFG [6] (m_{LFG}), and is used to calculate mass flowrate ($\dot{m}$) of condensate as defined in Equation (1):

$$\dot{m}_{cond} = \dot{m}_{LFG}(x_{140°F} - x_{90°F}) \qquad (1)$$

This shows that the condensate mass flowrate is roughly 7 gal/h of water for every 100 std. ft^3/min of LFG. The pumps are specified as low-flow positive-displacement pumps at continuous operation. These pumps are typically diaphragm-type with non-metallic internals.

LFG flaring

The minimum-effort form of LFG disposal is to incinerate the gas [7]. Smaller landfills do not produce enough high-value LFG to justify the investment for more expensive, yet potentially profitable, processing.

There are two types of flares: simple candle-type flares and the more expensive enclosed flares. Typically, environmental regulations require 95% or greater destruction and removal efficiency (DRE) of CH_4. The industry is moving away from candle flares because the temperature cannot be controlled enough to achieve the required DRE. An enclosed flare is a large vertical cylinder with multiple burners, temperature monitoring, air and fuel controls and heat conservation from refractory-lined walls. This design develops the maximum possible heat within the flare column.

Several factors (age of landfill, quantity of organic material, moisture, temperature and others) affect the quantity of LFG produced, as well as the composition of the LFG. At the beginning of the landfill's life, the composition is approximately 3 mol% CH_4 and 97 mol% CO_2, at 30 Btu/std. ft^3. Toward the end of its life, less LFG is produced, but at a better lower heating value (LHV) of 550 Btu/std. ft^3 (corresponding to 55 mol% CH_4 and 45 mol% CO_2).

Usually, enclosed flares are vendor-supplied and not designed by the process engineer. However, the process engineer should specify a maximum and minimum LFG flowrate, as well as a range of LFG compositions.

The process engineer should also ensure that flare systems are designed with auxiliary fuel injection to maintain the required DRE at the beginning of the landfill's life. The flare

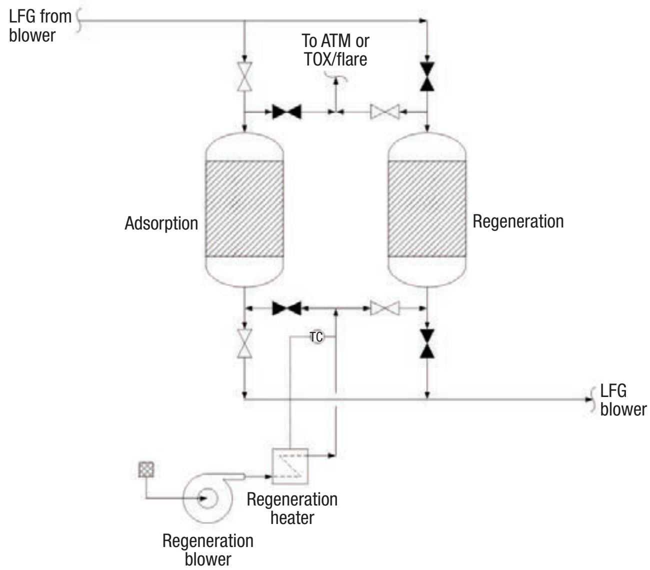

FIGURE 3. Temperature-swing adsorption (TSA) beds are used to remove water and siloxane content from LFG

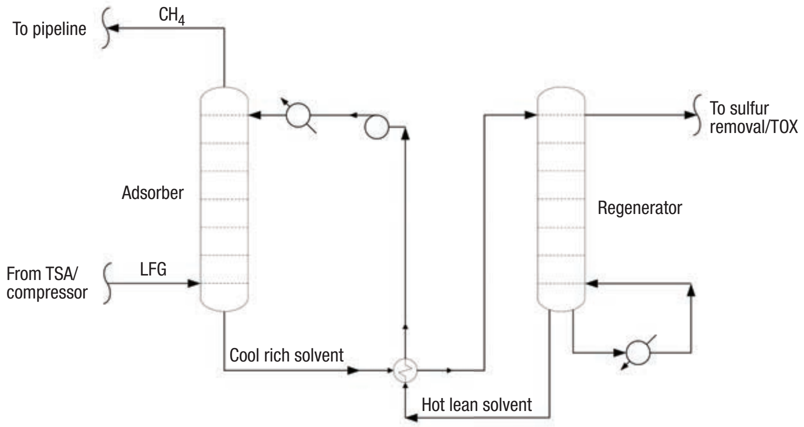

FIGURE 4. A solvent-circulation step treats the LFG's acid-gas content

stack should also be designed with burner tips that can be plugged, as well as adjustable air dampers, which maintain the DRE at the end of the landfill's life.

It should be noted that in most locations, removal of sulfur and nmVOCs is not required prior to flaring or direct use [*7*]. The requirement for removal is a function of the concentration of these substances, direct-user gas specifications and local regulations.

Direct-use methods and LFGTE

Combustion of LFG provides a great deal of heat duty for boilers, steam and electricity cogeneration and gas turbines, among other technologies. Most of the world's LFG direct use is electricity generation (LFGTE) [*3*].

LFG generator efficiencies are typically less than 40% because of the lower heating values of LFG compared to natural gas (around 550 Btu/std. ft^3 versus around 1,000 Btu/std. ft^3). High-efficiency generators can produce up to 400 kW per 100 std. ft^3/min of LFG.

LFG generator motors are susceptible to increased wear because, unlike natural gas, many LFG components can create hard deposits on the engine's pistons, cylinder heads, spark plugs and other motor parts. Siloxane, sulfur and halogenated hydrocarbons all can have a negative impact on the motor, as well as possibly exceed local regulations.

Pretreatment of the LFG and regular maintenance will prevent decreased engine life and performance. However, the process engineer's capex versus opex analysis could consider that more frequent engine maintenance may be acceptable as a substitute for a siloxane removal system.

Siloxane and water removal

Siloxanes are a type of silicone polymer, and when present in LFG, cause severe mechanical problems in the internal combustion engines of the generators. Silicon dioxide is the main siloxane combustion product, and it causes deposits of hard scale. Worse yet, landfills with metal content (such as iron or aluminum) will form hard, glass-like silicate deposits. These deposits significantly reduce the engine's life and significantly increase downtime due to maintenance. A common technology to remove siloxanes is temperature swing adsorption (TSA). In some cases, TSA units can be designed by process engineers, but they are usually vendor-supplied packages. Ref. 6 details the complete procedures for designing TSA units.

TSA systems (Figure 3) comprise two or more vessels (TSA beds) in parallel (one online for adsorption and the other offline for high-temperature regeneration), a regeneration blower and a heater. LFG passes through the adsorbent bed of the online vessel in downflow during the adsorption step. At the end of the adsorption step, the valves switch to set the offline vessel to online for adsorption and set the online vessel offline for regeneration.

In the regeneration step, hot regeneration gas (usually heated air) is blown through the adsorbent bed in an upflow pattern to swing the bed temperature, thus releasing the adsorbed siloxanes and water. Depending on local environmental regulations, the regeneration gas is vented, preferably to a thermal oxidizer (TOX). Industry experience suggests heating the adsorbent to about 400°F with 450°F gas. After the adsorbent has been regenerated, cool gas passes over the adsorbent to swing down the temperature to 100°F. The preferred adsorbent temperature is about 75°F or lower.

TSA adsorbents. The top adsorbent layer of the TSA bed is typically activated alumina or a molecular sieve for water removal, and the lower layer is silica gel for siloxane removal. Activated carbon was used for many years for siloxane removal. Now, however, the industry is using silica gel adsorbent because it has been demonstrated as the better siloxane adsorbent [*8*]. Activated alumina or molecular sieves are typical adsorbents for moisture adsorption. These allow silica gel (an excellent desiccant) to adsorb siloxanes selectively over water.

Adsorbent vessels are specified with a low length-to-diameter ratio to operate within a balance between a low pressure drop and minimum mass flux. The standard maximum pressure drop should not exceed 0.33 psi/ft across the bed. A low overall ΔP across the bed en-

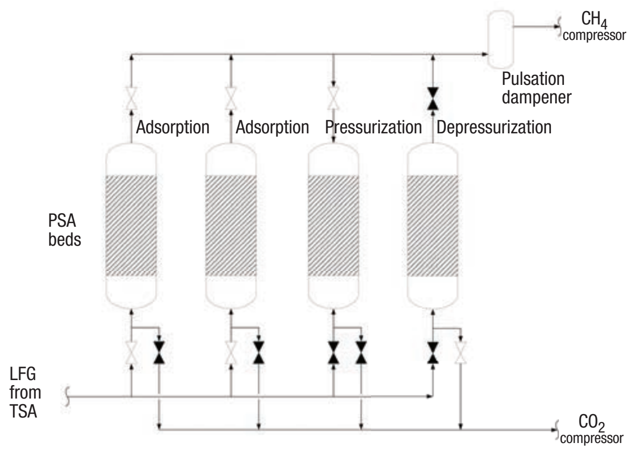

FIGURE 5. PSA units are used to absorb carbon dioxide from the LFG stream

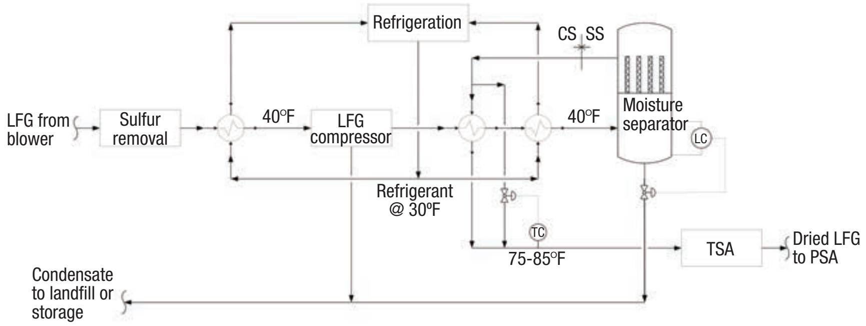

FIGURE 6. **LFG is chilled to help remove any remaining condensate, and also to relieve the power load on the compressor**

sures that the adsorbent particles are not crushed.

The minimum mass flux across the bed should exhibit a particle Reynolds number (Re_P) greater than 25. The high Re_P ensures adequate turbulence for best adsorbent effectiveness. The total quantity of each adsorbent required is calculated based on the total mass of water and siloxane to be removed against the adsorption capacity and saturation-zone efficiency of each media. TSA dryers are designed to lower the dew point to –40°F. Industry experience indicates that about 8 lb of water are adsorbed per 100 lb of fresh activated alumina, and about 4 lb/100 lb after 4 years. About 1 lb of siloxane is adsorbed per 100 lb of silica gel.

Typically, siloxane concentration can be estimated at a conservative 2,000 to 3,000 ppmw. However, the actual concentration should be determined by gas analysis. Note that while there are techniques to analyze the siloxane concentration, there is no standard testing method.

Theoretically, adsorbent layers are divided into a saturation zone at the top of the bed and a mass transfer zone below. The mass transfer zone is the layer of the bed where the water and siloxane are adsorbed, and the saturation zone is the layer where the adsorbent is fully loaded. As water and siloxane are adsorbed, the saturation zone increases and the mass transfer zone "moves" down the bed. The repeated cycle of adsorption and regeneration throughout the life of the bed reduces the adsorbent efficiency.

LFG to pipeline-grade natural gas

Processes that convert LFG to pipeline-grade natural gas are complex and require high-purity product. Purification requires compression of the LFG, then removal of moisture, siloxanes, CO_2 and inert substances.

Pipeline-grade natural gas characteristics are specified by local utilities. These specifications typically require that LFG be compressed to greater than 200 psig, and the CH_4 concentration must meet the heating value of about 1,000 Btu/std. ft^3. The total inert gases should not exceed 4 mol%. The gas must be free of all siloxanes, solids and impurities. H_2S must be limited to 4 ppmv and total sulfur (including H_2S) must be limited to 12 ppmv. A TSA removes siloxane and moisture. Acid-gas treating and pressure swing adsorption (PSA) are two common processes for CO_2 and sulfur removal.

In the acid-gas LFG purification process, a solvent is continuously circulated (Figure 4) through an absorber column and a regenerator column. Low-temperature lean solvent treats high-pressure acid gas in the absorber, and high-temperature, low-pressure rich solvent releases the concentrated acid gas to sulfur treatment.

The PSA LFG purification process (Figure 5) is a batch-wise, high-pressure adsorption of CO_2 on a PSA bed. The pressure swings low in the PSA bed to release the CO_2.

Sulfur removal. One common technology used for sulfur removal is the adsorption of sulfur species on iron oxide, activated alumina or another porous metal catalyst. Adsorption units typically consist of two or more beds operated in parallel. Once sulfur nears its breakthrough point, the adsorption media is replaced. The media is then treated as hazardous waste.

Wet scrubbing, another sulfur-removal technology, is typically vendor-supplied and proprietary. Wet scrubbing chemically transforms the H_2S and mercaptans into elemental sulfur. The LFG stream is contacted with an aqueous iron chelate solution, where the sulfur is ionized into hydrogen and sulfide ions [9].

The chelate complex is regenerated by oxidation and is returned to the absorber. The elemental sulfur can be sold to the fertilizer industry.

LFG compression and dewpoint depression. Sulfur-free LFG at 100% relative humidity should be chilled to 40°F (Figure 6). The chilled LFG is then compressed by a vendor-supplied compressor. Chilling the LFG to 40°F upstream of the compressor serves a dual purpose. First, any remaining aggressive condensate is knocked out for increased reliability of the compressor. Second, lower temperatures decrease the horsepower required by the compressor.

Hot, high-pressure LFG from the compressor should be chilled and dried through a coalescing moisture separator (or similar) to 40°F dewpoint. Typically, these separators experience a pressure drop of less than 20 in. H_2O. The condensed moisture is blown down by on-off level control at high or low liquid levels.

The cold, dried LFG is warmed against hot LFG from the compressor. A temperature-control bypass valve is sized for about 30 to 40% of the total flow. About 75°F (or lower) is

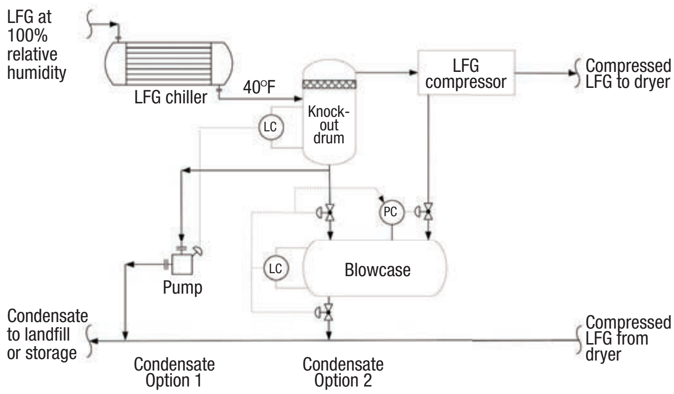

FIGURE 7. **Larger LFG plants may use a blowcase configuration to help collect liquid**

the preferred temperature range for TSA adsorbents. At the outlet of the moisture separator, the metallurgy can be downgraded from stainless steel to carbon steel [*5*].

CH_4 and CO_2 are separated in the PSA by adsorption of CO_2 from high-pressure LFG. The PSA vendor specifies the minimum required pressure (typically 120 psig) to achieve >99% CH_4 in the pipeline gas.

Blowcase operation. As discussed, the LFG from the blower is chilled to 40°F upstream of the compressor. This condenses the majority of the humidity (roughly 2 gal/h per 100 std. ft^3/min), which collects in the compressor knockout drum. One control strategy for condensate disposal is to pump the condensate to the landfill or storage via on-off level control at high or low liquid levels.

Another strategy is to collect the liquid in a small vessel called a blowcase and blow it down using on-off level control (Figure 7). During normal operation, the knockout-drum drain valve to the blowcase is open and the blowdown valves are closed. At the blowcase high-level signal, the inlet valve is closed and the blowdown valves are opened. The condensate is blown down with compressed LFG. At low liquid-level signal, the blowdown valves are closed and the drain valve is opened, which depressurizes the blowcase to the knockout drum. The process engineer should consider slow-opening valves to limit the blowdown rate and the impact of pressurization. The engineer must design the blowcase for cyclic service, because of the repeated operation of pressurization and depressurization.

Solvent absorption. In the acid-gas LFG purification process, high-pressure LFG contacts a low-temperature amine (or other solvent) in an absorber column. Lean solvent absorbs moisture, CO_2, sulfur and inert gases from the LFG. Rich solvent passes to a low-pressure, high-temperature regenerator, which separates the absorbed CO_2 and sulfur. The lean solvent is circulated through the absorber, and the acid gas passes to a sulfur treatment process. Note that siloxane is not absorbed.

Methane recovery with PSA. A PSA system (Figure 5) operates on the same principle of adsorption and desorption as the TSA. However, the PSA adsorbs at high pressure and releases at low pressure. In a PSA, the smaller molecules are adsorbed and the larger molecules pass through the beds. Methane is a larger molecule (3.8 Å) compared with nitrogen (3.6 Å), O_2 (3.5 Å), CO_2 (3.4 Å) and water (3.0 Å). Zeolite 13X (a crystalline polymer) with a pore size of 3.7 Å is usually selected by the PSA vendor to adsorb the inert substances and pass the methane to the pipeline.

The PSA unit is a complex vendor package with a sequence of switching valves that control the pressurization, depressurization and adsorption steps (Figure 5). The PSA beds' valves open and close to control the steps at each bed. In the depressurization step, the vessel inlet valve and the CH_4 compressor's suction valve close. Then the suction valve to the CO_2 vacuum compressor opens. The very low pressure regenerates the bed by releasing all inerts adsorbed on the media. In the pressurization step, the inlet valve and compressor suction valve close and the outlet valve opens. This floods the bed with high-purity CH_4. Once pressured, the inlet valve opens and the adsorption step begins.

The process engineer should specify the PSA system for at least 97% CH_4 purity (based on local utility requirements) and 85% recovery. PSA technology can achieve greater than >99% purity and 95% recovery. The natural gas from the PSA should be compressed to pipeline requirements, typically 200 psig or greater, also based on local utility requirements.

CO_2 destruction by thermal oxidation. PSA depressurization releases inert gases and 4 to 10% CH_4. Environmental regulations typically do not allow release of these inert gases and CH_4 to atmosphere. This low-BTU gas is then destroyed in a very high-temperature thermal oxidizer (TOX), which is also complex and typically supplied as a vendor package. The TOX operates under a similar principle as a high-temperature enclosed flare. The TOX burns the CH_4 at very high DRE to meet environmental regulations. A very high combustion temperature is required because the high concentration of CO_2 significantly decreases the DRE of CH_4.

In poorly designed or poorly operating TSA systems, some liquid may remain in the LFG and thus may be adsorbed in the PSA. To capture the liquid droplets and prevent fireballs in the TOX, a pulsation dampener (as shown in Figure 5) should be considered. Any remaining water is adsorbed in the PSA. Liquid droplets are knocked out in the pulsation dampener, which should be sized for droplets in the range of 300 to 600 µm in diameter [*11*]. Because the PSA depressurization steps are not continuous, a pulsation dampener reduces the high surge of CO_2 to the TOX at the start of the depressurization step. ■

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References

1. Agency for Toxic Substances & Disease Registry, Landfill Gas Primer, U.S. Department of Health and Human Services, Nov. 2001.
2. U.S. Code of Federal Regulations, Title 40 — Protection of Environment, Part 258 — Criteria for Municipal Solid Waste Landfills, July 2012.
3. Arnold, M., Reduction and monitoring of biogas trace compounds, VTT Technical Research Centre of Finland, Aug. 2009.
4. U.S. Army Corps of Engineers, Landfill Off-Gas Collection and Treatment Systems, Department Of The Army, EM 1110-1-4016, May 2008.
5. Hansen, D.A., Puyear, R.B., "Materials Selection for Hydrocarbon and Chemical Plants," CRC Press, 1st edition, Aug. 1996.
6. Gas Processors Suppliers Association, Engineering Data Book, 12th edition, 2004.
7. Scottish Environment Protection Agency (SEPA), Guidance on Landfill Gas Flaring, Nov. 2002.
8. Schweigkofler, M., Niessner, R., Removal of siloxanes in biogases, *Journal of Hazardous Materials.*, 2001.
9. Wang, L.K., Pereira, N.C., Hung, Y.T., "Handbook of Environmental Engineering, Volume 2: Advanced Air and Noise Pollution Control," Humana Press, Nov. 2004.
11. American Petroleum Institute, Pressure-Relieving and Depressuring Systems, API STD 521, 6th edition, Jan. 2014.

Author

Babak Firoozi is the vice president of HVAC Engineering at A/C Control, Inc. (2355 Westwood Blvd #145, Los Angeles, CA 90064, Phone: (310) 909-4814; Email: babak@ac-control.com). He previously served as a process director at Oilcor, Inc. Firoozi's process engineering experience includes landfill gas processes, downstream refining and process simulation. He earned his B.S.Ch.E. from University of Baja California, Mexico, and he earned his M.S.Ch.E. from California State University. He also is a registered professional engineer in California.

Economic Indicators

2019 2020 2021

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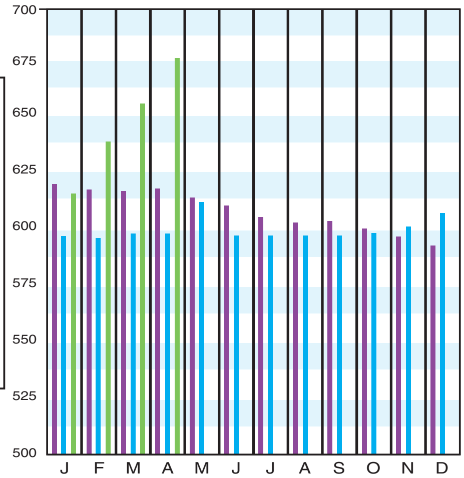
CHEMICAL ENGINEERING PLANT COST INDEX (CEPCI)

(1957–59 = 100)	Apr. '21 Prelim.	Mar. '21 Final	Apr. '20 Final
CE Index	677.7	655.9	595.6
Equipment	837.4	808.5	723.4
Heat exchangers & tanks	723.6	698.5	620.6
Process machinery	854.8	792.5	725.4
Pipe, valves & fittings	1,129.5	1,094.3	944.3
Process instruments	495.3	474.6	411.3
Pumps & compressors	1,111.4	1,111.9	1,086.3
Electrical equipment	593.3	586.3	561.3
Structural supports & misc.	904.5	877.3	777.8
Construction labor	340.2	333.9	332.6
Buildings	710.6	678.7	591.0
Engineering & supervision	310.3	310.2	313.0

Annual Index:
2013 = 567.3
2014 = 576.1
2015 = 556.8
2016 = 541.7
2017 = 567.5
2018 = 603.1
2019 = 607.5
2020 = 596.2



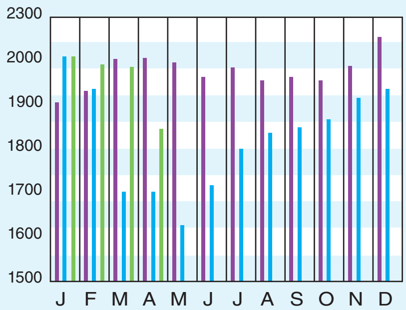
Starting in April 2007, several data series for labor and compressors were converted to accommodate series IDs discontinued by the U.S. Bureau of Labor Statistics (BLS). Starting in March 2018, the data series for chemical industry special machinery was replaced because the series was discontinued by BLS (see *Chem. Eng.*, April 2018, p. 76–77.)

CURRENT BUSINESS INDICATORS

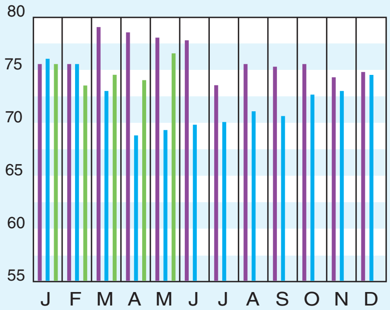
	LATEST	PREVIOUS		YEAR AGO
CPI output index (2017 = 100)	May '21 = 96.0	Apr. '21 = 95.0	Mar. '21 = 95.0	May '20 = 85.3
CPI value of output, $ billions	Apr. '21 = 1,837.7	Mar. '21 = 1,761.8	Feb. '21 = 1,761.8	Apr. '20 = 1,428.3
CPI operating rate, %	May '21 = 76.5	Apr. '21 = 75.6	Mar. '21 = 75.6	May '20 = 67.3
Producer prices, industrial chemicals (1982 = 100)	May '21 = 299.4	Apr. '21 = 240.0	Mar. '21 = 240.0	May '20 = 200.0
Industrial Production in Manufacturing (2017 =100)*	May '21 = 98.2	Apr. '21 = 96.8	Mar. '21 = 96.8	May '20 = 83.1
Hourly earnings index, chemical & allied products (1992 = 100)	May '21 = 195.9	Apr. '21 = 194.3	Mar. '21 = 194.3	May '20 = 192.2
Productivity index, chemicals & allied products (1992 = 100)	May '21 = 92.5	Apr. '21 = 92.1	Mar. '21 = 92.1	May '20 = 88.1

CPI OUTPUT INDEX (2017 = 100)†

CPI OUTPUT VALUE ($ BILLIONS)



CPI OPERATING RATE (%)



*Due to discontinuance, the Index of Industrial Activity has been replaced by the Industrial Production in Manufacturing index from the U.S. Federal Reserve Board.
†For the current month's CPI output index values, the base year was changed from 2012 to 2017
Current business indicators provided by Global Insight, Inc., Lexington, Mass.

CURRENT TRENDS

The preliminary value for the *CE* Plant Cost Index (CEPCI; top) for April 2021 (most recent available) continues the string of sizeable monthly increases. In April, large upticks were observed in the Equipment, Buildings and Construction Labor subindices, while the Engineering & Supervision subindex saw a slight rise. The current CEPCI value now sits at 13.8% higher than the corresponding value from April 2020. The Current Business Indicators (middle) changed the base years for two of the indices. The U.S. Federal Reserve (www.federalreserve.gov), the source of the data, changed the base year of the CPI Output Index to 2017 (previously, it had been 2012), and also changed the Industrial Production in Manufacturing base year to 2017 from 2012.